CESIUM-137 FALLOUT IN INDIANA SOIL

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ABSTRACT

DISSERTATION: CESIUM-137 FALLOUT IN INDIANA SOIL

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Atomic weapons testing during the Cold War and accidents at nuclear power plants have resulted in the release of radioactive fallout over great distances. Little is known about levels of fallout deposited in Indiana. The reported study sampled soil in all 92 Indiana counties to determine the present level of cesium-137 from the 2 to 12 centimeter depth from previous nuclear tests and other nuclear releases. A total of 67 samples were collected from forested areas and 25 from grasslands, both undisturbed since 1940, along with four controls from crawl spaces. Greater Cs-137 retention occurred in the forested areas at approximately a 2:1 ratio. Other parameters investigated included soil clay content, rate of rainfall, and soil pH. Each variable was examined for possible statistical correlation with Cs-137 retention. Both clay content and combined clay content/rainfall were significantly ($p < 0.05$) correlated with soil Cs-137 levels. The four controls showed very low values of Cs-137 indicating the movement of sub-micron sized fallout into areas considered safe from fallout. The Cs-137 data from this study will serve as a reliable baseline of Cs-137 levels in the event of a future release of fallout.

Keywords: Indiana; cesium-137; fallout

DEDICATION

This dissertation is dedicated to Sophie Abbott.

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CHAPTER 1: INTRODUCTION

On July 6, 1962, the last above-ground nuclear detonation occurred at the Nevada Test Site. With the release of a 104 kiloton weapon, 9.2 million cubic meters of soil were lifted from the desert floor. Most of the material, made radioactive by the detonation, returned to earth nearby. Some of the fallout, however, traveled great distances; modest quantities were measured in two Indiana counties as the cloud moved to the east. This deposition imparted an estimated minor long-term exposure to residents. Nuclear weapons testing by the United States and other nations produced about two hundred such deposition events. The geography of the United States favors fallout deposition on the Midwest and the eastern half of the United States, however, nearly all fallout sampling occurred West of the Mississippi as contemporary studies did not yet recognize lower levels of fallout. Very little contemporary research has occurred on this topic.

The history of modern society demonstrates many examples of the rapid development of technology in engineering, energy, and chemistry. Examples include the rise of coal for generating power, in steelmaking, and the development of synthetic organic chemicals. These and other new developments have produced demonstrable benefits; however, many of these same innovations have created consequences which the developers minimized, ignored, or had no idea of its impact on the environment. Our modern understanding of coal combustion, the use of the insecticide DDT, and CFCs (chlorofluorocarbons) provide examples of initial adoption with great benefit and later lessons in unintended or under-appreciated impact. Cutbacks in use of these items have resulted in measureable local, regional, and even global environmental improvements.

In 1939 Albert Einstein wrote a letter to President Franklin Roosevelt concerning the possibility that Germany might develop an atomic weapon at the start of World War II. This led

to the development of atomic weapons by the Manhattan Project. The first atomic weapon detonation at the Trinity Site in New Mexico in July 1945, and two other weapons over Japan at the conclusion of the war demonstrated temporary United States and United Kingdom hegemony in this field. This leadership would soon fade due to the work of Soviet Union spies and others and by 1949 the Soviet Union tested their first weapon. In 1960 France tested an atomic bomb and was followed by China in 1964. By 2015 about a dozen nations had acquired nuclear technology and built and tested weapons with increasing power.

The legacy effects from the mining and purification of uranium resulted in metal and acid poisoning of large areas of soil and groundwater at many sites such as Hanford, WA. Some of these effects, though known at the time, were of less concern than supporting the war effort. During the development of atomic power plants in the 1950s, methods and requirements to control wastes from this kind of work resulted in early efforts to minimize or reclaim toxins before entering the environment.

The underappreciated effects of nuclear materials did not rise to a level of greater concern until the atmospheric atomic weapons releases in the post-World War II era. Beginning with United States tests in the Western Pacific Ocean and continuing with other detonations at the Nevada Test Site led to the realization of global impacts. The two leading nuclear nations, i.e., the United States and the Soviet Union, ceased above-ground testing in 1962; however, France, China and others continued atomic detonations into the 1970s. Since then India, Pakistan, and North Korea have tested nuclear weapons. The fear and mistrust between the United States and the Soviet Union led to the buildup of weapons by both countries and several others as well.

Large-scale releases from damaged commercial nuclear power reactors have produced many similar effects as those from atomic weapons. The Chernobyl (1986) and Fukushima

(2011) disasters released massive quantities of radioisotopes into the atmosphere. The behavior of this fallout, however, differed in terms of distribution patterns.

Several factors complicated scientific understanding of the quantity and characteristics of radioactive fallout from atomic weapons: early radiation meters lacked enough precision to measure low levels of fallout and our understanding of the atmosphere remained very limited before 1960. Although the United States government tested soil and water at many locations to determine quantities of fallout, most of the Midwestern States received little attention.

Objectives:

The purpose of the reported research activity was to determine the degree of radioactive fallout, primarily as cesium-137, remaining in Indiana soils undisturbed since <1940. The null hypothesis for this work states that the mean retention in long-term forests and long-term grasslands are equal. The alternative hypothesis would find significant difference between these two groups. Specific objectives were to:

1) Sample and determine levels of Cs-137, a long-lived and unique result of atomic releases at a fixed depth of 2 to 12 cm in all 92 Indiana counties from locally level locations in long term undisturbed forest and grassland locations.
2) compare Cs-137 activities in the soil of Indiana forest and grasslands, with the hypothesis that long term forests have retained a greater measure of this isotope;
3) assess Cs-137 retention in soil as a function of rainfall level; and soil properties including clay content and pH.
4) compare retention of lead-210 and potassium-40 with that of Cs-137;
5) formulate a set of ideas to enhance teaching concepts involving nuclear hazards, fallout, etc. from nuclear releases.

CHAPTER 2: REVIEW OF LITERATURE

Fallout Defined

About 10% of the total energy from a nuclear detonation occurs as fallout, that is, fine particles of radioactive dust that settle back to earth over a period of minutes to years (Pichtel, 2016). This radiation is derived in part from fissionable fuel material in the weapon, but largely due to the radioactivity of the fission products generated, including irradiated soil and moisture at the point of detonation (i.e., ground zero). Some 300 different radionuclides representing 40 elements originate from the detonation of a fission-type nuclear weapon. As an example, uranium-235, when fissioned, or split, produces many characteristic products, most of which become radioactive for distinct times. Equation 1.0 shows one possible fission reaction, where U-235 converts to form strontium-95 (^{95}Sr), xenon-139 (^{139}Xe), and two neutrons (η), plus energy (Glasstone and Dolan, 1977):

$$235U + \eta \rightarrow 95Sr + 139Xe + 2\eta + 180\ MeV \qquad (1.0)$$

Radioactive materials blasted high into the atmosphere by the force and heat of a nuclear detonation can travel hundreds of miles before falling to earth, depositing radioactive contamination across thousands of square kilometers. The intensity and duration of contamination from fallout varies with the yield of the weapon, its proximity to the ground surface at the time of detonation, and weather factors (Pichtel, 2016).

The development of our understanding of the fate of radioactive fallout, including cesium-137, followed a decade-by-decade improvement in both scientific understanding and instrument sensitivity following World War II. Security requirements and wartime exigencies

during World War II and for the decade following limited the sharing of information about these weapons and their effects. In addition, however, the massive data compiled from the detonation of the first three atomic weapons in 1945, the first at the Trinity Site in New Mexico, and the other two on Japan near the end of the war, overlooked the significance of the long-distance distribution of micron-sized particles.

In retrospect, United States scientists did not fully understand or consider the long-term effects to public health and the environment from either weapons production or from the radioactive material produced by atomic detonations. The understanding of radiation effects developed during four distinct and overlapping phases. These four phases include: (1) time prior to the advent of accurate instrumentation or weather information or until 1960; (2) when health concerns dominated studies from about 1953 onward; (3) the period after 1962 and beyond, when scientists refined previous releases and initiated studies of fallout impacts on soil; and (4) the present time, beginning with the 1986 Chernobyl reactor disaster and the more recent 2011 Fukushima reactor failure (Ashraf et al., 2014). These reactor failures, due to their magnitude and the persistence of materials released, resulted in new scientific interest using significantly advanced instrumentation, including satellite measurements. Data analysis, especially for the Fukushima event continues to the present time.

Earliest Atomic Tests

Scientists at the Trinity (NM) site recorded the details of the first detonation (Fig. 1). Following the detonation field surveys measured the extent of the fallout as scientists then understood it, but did not realize that smaller particles would be deposited at extended distances and at later times. Similar surveys following the atomic bombing of Hiroshima and Nagasaki, Japan, would follow;

likewise, these surveyors did not comprehend the full distribution of fallout (Glasstone and Dolan, 1959).

OPERATION TRINITY

	MST	GMT
DATE:	16 Jul 1945	16 Jul 1945
TIME:	0529	1229

Sponsor: Los Alamos Scientific Laboratory
SITE: 57 miles Northwest of Alamogordo, New Mexico
Coordinates: 33° 40' 31" N 106° 28' 29" W

Total Yield: 19 kt

Site elevation: 4,624 ft

HEIGHT OF BURST: 100 ft
TYPE OF BURST AND PLACEMENT: Tower bust

FIREBALL DATA:
Time to 1st minimum NM
Time to 2nd minimum NM
Radius at 2nd maximum NM

CLOUD TOP HEIGHT: 35,000 FT MSL
CLOUD BOTTOM HEIGHT: 10,600 MSL

CRATER DATA:
DIAMETER 1,100 ft
DEPTH: 9.5 ft

Figure 1. Details of Trinity Detonation providing perspective on resulting damage (Gladeck, 1996) Note: MSL refers to mean sea level

On the day of the Trinity release in July 16, 1945, military survey teams working at some distance from ground zero measured radioactive fallout. The full import of this phenomenon was not apparent as teams of surveyors presumed that the rapid decline in readings over just a few hours implied that radioactive material would dissipate completely. Few realized that some products from the detonation would persist, among these, Cs-137 which has a half-life of slightly over 30 years. The radioactive meters in use at the Trinity test did not have the sensitivity needed to measure the lingering fallout (Fig. 2). The readings of Trinity fallout were mapped using

values in Roentgens per hour, which has less precision than units in use today (Widner and Flack, 2010). At the time of the Trinity test, there was no comprehension that micron-size and smaller fallout could move markedly beyond the area of the map.

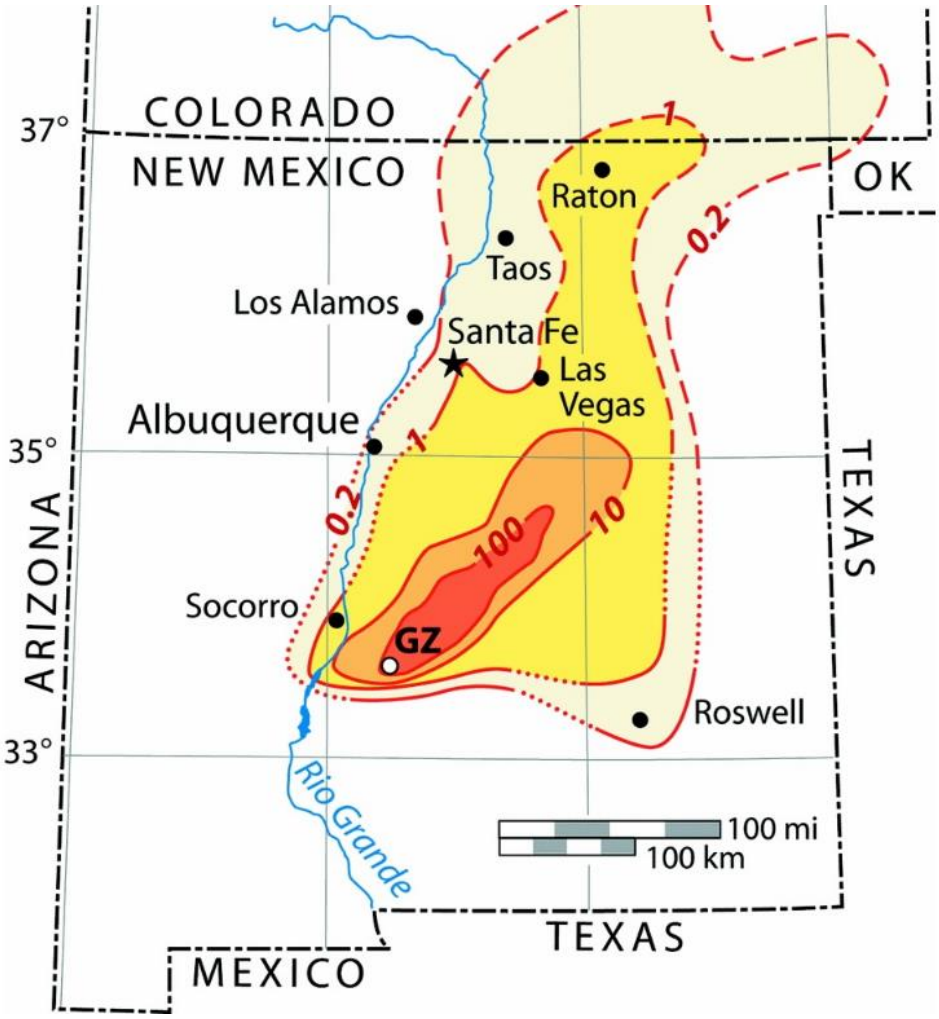


Figure 2. Map of the Trinity detonation and local fallout plume measurements in R/hr (Widner and Flack, 2010).

The combined pressure and temperature from the Trinity Test appear in Fig. 3. The unique combination of extremely high temperatures and pressures over a short period produced fine fallout particles which are subsequently distributed to high latitudes (Bonamici et al., 2017).

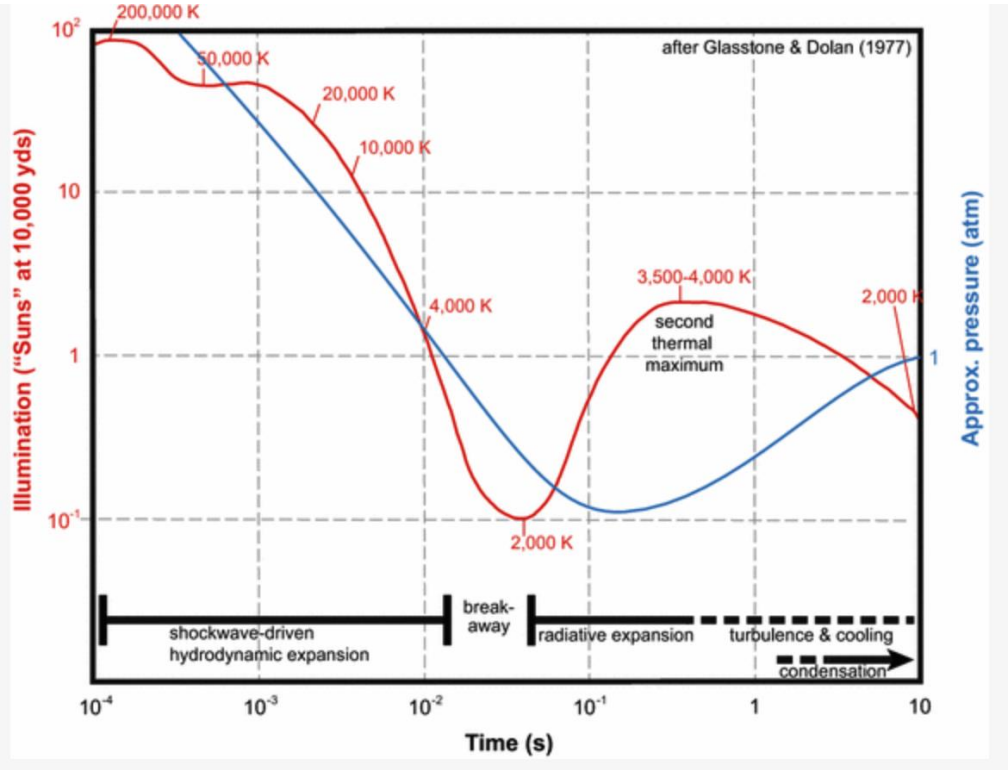


Figure 3. Illumination from a nuclear detonation as a function of temperature and pressure. Time ranges from 10^{-4} to 10 seconds after release (Glasstone and Dolan, 1997).

Radiation units have evolved since the Trinity test. The so-called 'Standard Units' predominated in the scientific literature before 1980, and Systeme Internationale (SI) units appear in most literature since then. For most of the reviewed literature, the term 'Dose' refers to potential dose to organisms measured as a rate, e.g., per hour by a meter, while the term 'Dose Equivalent' refers to the long-term accumulated human exposure, usually verified by some kind of dosimeter (Table 1). The reading from personal dosimetry determines the dose equivalence in real time, but before 1958 most tests either estimated the dose equivalence or conducted dosimetry on 1 of every 40 or more persons (Blake, 2017).

Table 1: Comparison of radiation units

Term	Use	Traditional System*	Systeme Internationale
	Older method used	Roentgen, R	1 Coulomb per kilogram
Exposure	For surveys		
Dose	Used now for surveys	Radiation Absorbed Dose, Rad	Gray(Gy) = 100 RAD
Dose Equivalence	Medical or dosimetry	Radiation Equivalent Man, REM	Sievert (Sv) = 100 REM

* Measurements during U.S. weapons tests used the Traditional System.

Currently, only laboratories use the Roentgen and Coulomb per kilogram units. Hand-held radiation meters use either milliRad (mRad) per hour or the equivalent SI analog, milliGray (mGy) per hour, which became common after 1980. Health physicists and medical personnel worldwide limit effective radiation dose, or cumulative exposure to people by controlling exposure to two limits: one by the hour (2 mRad per hour or 0.02 mGy per hour) and the other by annual exposure (not more than 100 milliREM (mREM) or 1 milliSievert (mSv) per year). Those working with radiation (e.g., workers at a nuclear facility) can receive a higher dose equivalence during employment, yet most employers prefer radiation workers to stay close to the limits established for the public. Radiation workers can receive a total of 5,000 mRem (50 mSv) for a year; however, some countries now limit radiation workers to not more than 2,000 mREM (20 mSv) in any year and not more than 5,000 mREM (50 mSv) in not more than one year in three.

In the United States, both the civilian use of radiation and ongoing weapons-related work rely upon limits set by the U.S. Nuclear Regulatory Commission (NRC) and the U.S. Department

of Energy (DOE), respectively, as found in Title 10 of the Code of Federal Regulations. An elaborated version of these standards appeared in the US NRC guidance document NUREG 1736 published in 2001. For emphasis, the "1" value shown in Fig. 2 (Trinity site detonation map), touches both Santa Fe and Las Vegas, and represents 1,000 mRAD per hour or 10 mGy; these values are well above the limits for the public or even radiation workers since 1958.

In the case of fallout from a weapon, detonation must occur on the ground surface or near enough so that the characteristic fireball interacts with surface materials including soil, water, vegetation, buildings, and roadways. The enormous blast pressures and significant heat will crush, burn, and vaporize surface material to predictable distances depending on size of the weapon, altitude of detonation and topography below the detonation point. The pulverized, superheated material then rises into the atmosphere. The conversion of this debris into radioactive fallout has begun (Reed and Stillman, 2009; Rhodes, 2012).

Nuclear Weapon Designs

Nuclear weapons produce a tremendous explosive force which is generated from the fission (splitting) or fusion (joining) of atomic nuclei to release energy much more powerful than from any known chemical explosive. This explosive power, or yield, of a nuclear weapon typically is compared to the force from the explosive trinitrotoluene (TNT) that would release an equivalent amount of energy. Typically units were originally thousands of tons of TNT (kilotons, kt). The most powerful weapons measure the yield in millions of tons of TNT (megatons, Mt). Weapons often over- or under-yielded by as much as 33%, and the Castle Bravo over-yielded by 400%.

Nuclear Weapons Tests

The first of the fission devices (July and August, 1945) yielded in the range of 10–20 kt. Substantially greater yields occurred for the fusion weapons that followed in 1952 (Rhodes, 1986). In 1952, the U.S. detonated a 10.4 megaton weapon which produced approximately 1,000 times greater force than the weapon used at Hiroshima. This device illustrated the magnitude of effect of this class of so-called thermonuclear weapons. Green (1962) described the force of the detonation as well as how fallout would eventually return to earth (italics added for emphasis):

> The Eniwetok explosion mentioned above wiped out a small island (Elugelab) and left a crater a mile in diameter and 170 feet deep. This is equivalent to the vaporization of *50 million tons of earth which was carried up with the fireball in the usual mushroom shape as far as 25 miles into the stratosphere*. (As a comparison, we might remember the volcanic eruption which destroyed the island of Krakatoa in 1883. Lava and ash amounting to somewhere between 100 million and 20,000 million tons were ejected into the atmosphere. *About one third fell within 30 miles, another one-third within 2000 miles and the rest within about 3 years.* The high-speed equatorial wind which circulates in the stratosphere is known as the Krakatoa wind as a result of observing the fate of the debris. The velocity of this wind was checked by observing the results of the Marshall Is., 1956, high yield explosions). (Green, 1962)

Following the detonations on Japan in August 1945, long-term studies of the survivors and structures began. Studies continued during another round of tests in the Marshall Islands in the Western Pacific. The Marshall Islands tests began in 1946 and continued until 1958 with a total of 62 weapons detonations, including 16 which yielded in the Mt range. The early detonations tested weapons effects against naval vessels and later evolved to improving weapons design (Tipton, 1981). This series proved tragic when a 1954 fusion test named Castle Bravo over-yielded at 15 Mt instead of 5 Mt, and along with an unexpected wind shift at altitude produced dramatic fallout precipitation over inhabited areas. Fallout moved directly east instead of north (Fig. 4) (Glasstone and Dolan, 1977).

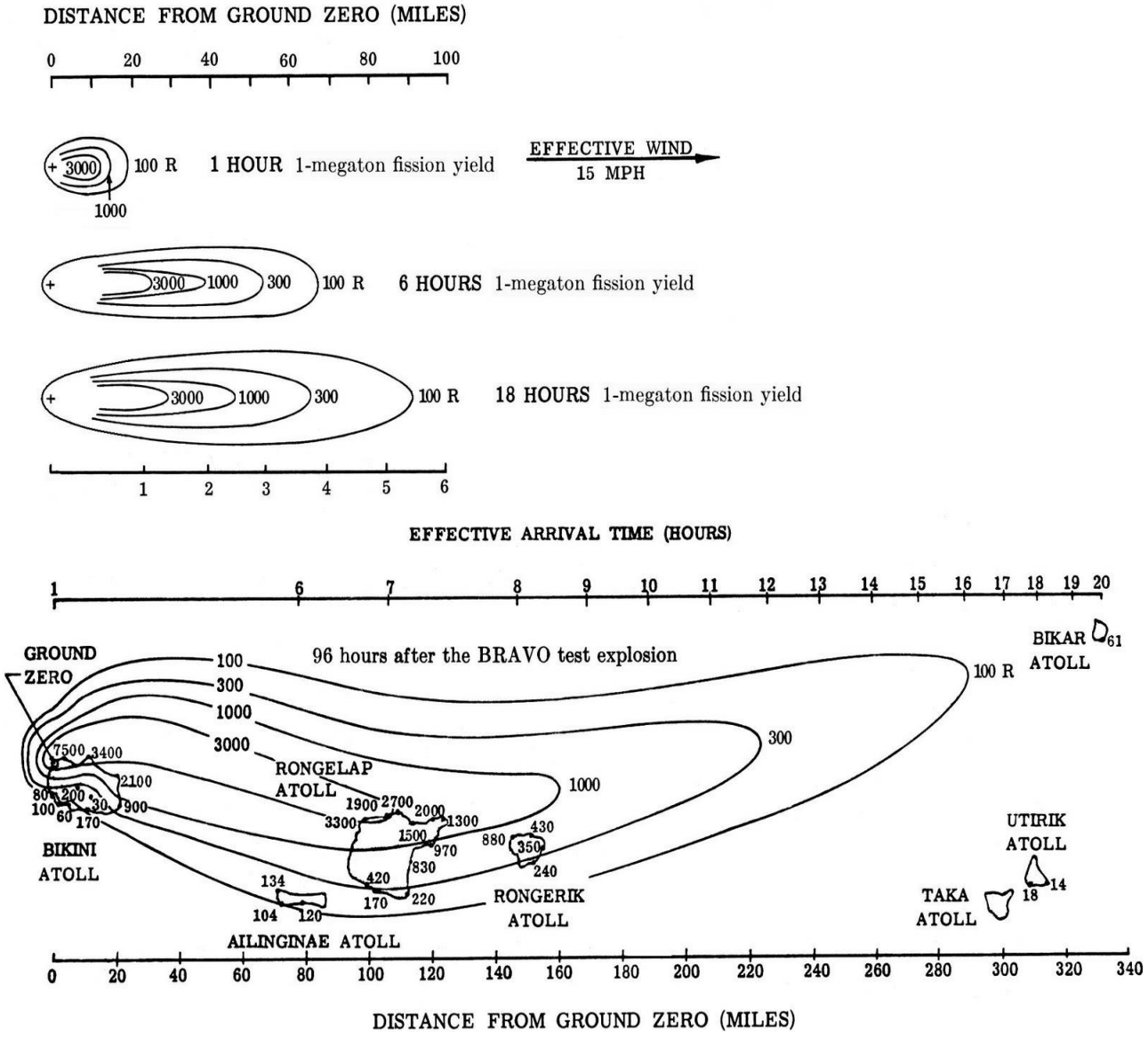


Figure 4. Fallout arrival times from the Castle Bravo (1954) test. The map in Fig. 4 shows contours in RAD per hour. Dividing the values by 100 results in conversion to SI units. Fig. 4 shows R/hr units, which, for survey purposes, equate to Rem/hr from a 1 Mt release, rather than the actual results of the Castle Bravo test of 15 Mt. Castle Bravo exceeded expectations by 400%.

At the time of the Castle Bravo test, the extensive fallout plume received scant public attention and the military dismissed this error as a weather oddity. In reality, many scientists and engineers committed serious errors. For example, the test over-yielded with the equivalence of

750 Hiroshima weapons. By 1982 the Defense Nuclear Agency unclassified and revised the details of what occurred and included more information including the total cost to the Marshallese Islanders and the Japanese fishing industry (Weisgall, 1994).

Unintentional Effects from Testing

Four groups suffered radiation exposures during the Castle Bravo test. Two of these involved U.S. military test participants; one group comprised Navy ships which recognized the approaching fallout cloud and sheltered indoors; the other involved a group of weather scientists who also sheltered in place. For Navy personnel on one vessel the recorded dose was 0.47 Sieverts (4.7 REM). The weather scientists on nearby Rongerik atoll who sheltered in place hold the record for the highest occupational dose (86 REM or 0.86 Sv) ever received within the military (Blake, personal communication, 2017). A response by Navy radiation scientists regarding this incident was published in *Science* in September 1955 (Andrews, 1955).

Two other groups were unaware of the hazard and suffered – the native population on Rongerlap atoll and Japanese fishermen on the fishing boat *Lucky Dragon* both suffered skin burns and other effects from fallout. The Navy evacuated the Rongerlap residents within a day, and allowed them to return from 1957 to 1959. The residents were evacuated a second time, and permanently, following another radiation survey (Tipton, 1981). The Rongerlap inhabitants have not lived on their former island home since, and 131 of those 256 exposed from Castle Bravo continue under U.S. DOE medical care. Several groups of Marshallese have received grants totaling nearly $759 million and foodstuffs from the U.S. Department of Agriculture to the present day (Schwartz, 1998).

The *Lucky Dragon* returned to Japan where one crewmember died from radiation exposure and the surviving crewmen spent 14 months recovering. A total of 457 tons of tuna on 563 Japanese fishing vessels was lost (Weisgall, 1994). Over the course of five years, the U.S. State Department and the Japanese government negotiated a no-fault settlement in which the former paid the Japanese government a sum of $2 million *ex gratia*, or no fault. Most of the money was transferred to the Japanese tuna industry while a portion went to the surviving crewmen of the *Lucky Dragon*. (Schwartz, 1998).

A comprehensive study by Cronkite et al. (1954) entitled, "Study of Response of Human Beings Accidently Exposed to Significant Fallout Radiation" addresses the health impacts of the Castle Bravo event. Subsequent work by the Defense Threat Reduction Agency (DTRA) continues. The Nuclear Test Program Review Office at DTRA continues to monitor the military weather personnel since the Castle Bravo test, including a recent series of blood tests to examine chromosomal indications of the Rongerik weather observers who received a dose equivalence of 86 REM (Tipton, 1981).

Later Atomic Tests, 1958 -1962

As weapons testing continued in the Marshall Islands, in 1950 the U.S. Department of Defense (DOD) partitioned Nellis Air Force Base, near Las Vegas, Nevada, to create the Nevada Test Site. One hundred tests occurred above-ground and 921 nuclear detonations occurred below-ground at the Nevada site. Underground testing limited observation by Soviet satellites or spies who might pick up residue or nearby fallout to ‘reverse engineer’ bomb ingredients via isotope ratio comparison. Reverse-engineering involves determination of isotope ratios of fission or fusion residues, which can be extrapolated to determine composition of a weapon. The last large

detonation took place at the Nevada Test in July 1962; minor tests and related work continue to the present. All tests included acquisition of significant details, including measurement before, during and post-release. Records of the above-ground Nevada tests include fireball characteristics, cloud dimensions, mushroom cloud tops and bottoms, as well as measurements of the speed of cloud rise, and post-blast effects analysis. Multiple high speed photographs, many still classified, remain in the DTRIAC library.

As radiation instrumentation improved through the 1950s, the sensitivity of measurements also improved. Some studies focused on radiation inducement of the soil and objects at ground zero and at specific distances from ground zero. Other studies addressed the mixing of fallout into weather patterns and still others examined the potential uptake of fallout products by plants and other organisms.

Other tests included testing survivability of trees, animals, military bunkers and buildings and several two-story homes, complete with mannequin families and household furnishings. The types of furniture fabric, the mannequins and household appliances also became survival test elements. This information was compiled to develop both military ‘hardening’ techniques and to develop information for the newly formed Civil Defense programs (Rowe, 1956).

An important aspect of the history of nuclear testing in both the Pacific and Nevada involved the data concerning the people involved in tests, and from plants and animals intentionally exposed. Such data was needed in order to learn more about survivability from a medical or even a military perspective. In one test at the Nevada site, thousands of soldiers pre-positioned in trenches as the 1953 shot ‘Simon’ detonated. One minute after detonation the soldiers left the trenches and moved directly into the area of the detonation and into fallout dust.

The soldiers carried three dosimeters, one in the helmet, one in a breast pocket, and one in a hip pocket (Massie et al., 1982). The full details of this report remained classified for 31 years.

As the magnitude of a weapon release increases significantly with the introduction of megaton weapons, Glasstone and Dolan (1977) calculated how detonation effects escalate as yield increases. These changes alter the dispersion of fallout into the stratosphere.

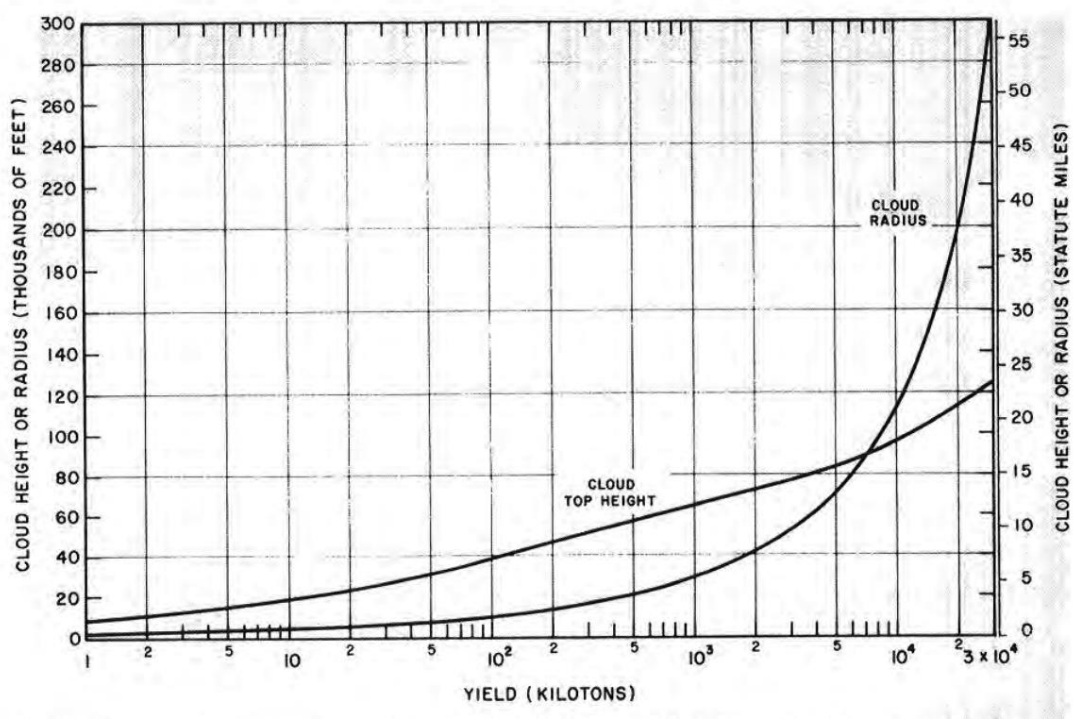


Figure 5. Chart showing the yield characteristics of kiloton and megaton weapons (Glasstone and Dolan, 1977) Note: 10^3 represents 1 megaton; 10^4 represents 10 megatons.

The lack of knowledge on the size of fallout particles hindered our early understanding of fallout distribution. Glasstone and Dolan (1958) state that peak fallout would arrive within the first 30 days with greater deposits at 30 degrees N. latitude. Langham and Anderson (1958) had

interpreted fallout to predominate at 40 degrees N. latitude. By comparison, the southern hemisphere showed a lower percentage of fallout as noted during worldwide sampling by the Environmental Measurements Laboratory of the U.S. DOE (Beck, personal communication, 2016). Fallout studies from any one event became more difficult to study during this time as the United States and the Soviet Union rushed new weapons into development and testing just as other countries, e.g. France and China, developed and tested nuclear weapons. Even after the end of testing larger weapons by the United States and the former Soviet Union, others contributed to the release of additional fallout (Fig. 6).

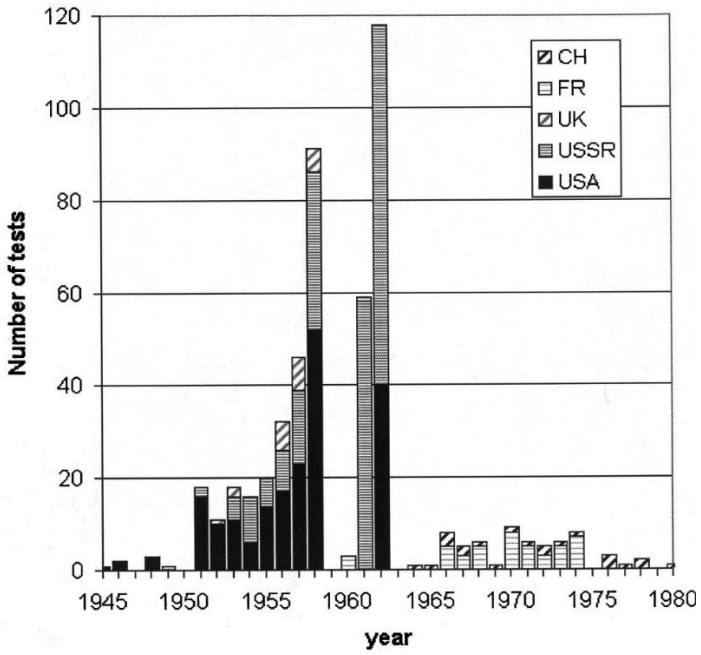


Figure 6. Atmospheric atomic weapons, by year and by country.

Fig. 6 does not include low kiloton Indian and Pakistani tests in the Southern Hemisphere. North Korean tests to date have occurred underground and do not appear on this chart (Beck and Bennett, 2002).

Atmospheric Dispersion of Fallout

Many aspects of atomic tests remained classified through most of the Cold War, including the behavior of fallout in the upper atmosphere. Klement (1965) reported on tests at high altitude (Fig. 7). Over time, scientists discovered that the several components of fallout, including Cs-137 and Sr-90, due to their boiling temperatures, condensed to particles in the sub-millimeter size when lofted to higher altitudes and remained aloft for years depending largely on particle size (Klement 1965; Libby, 1958).

The sampling at altitude shown in Fig. 7 took place as part of Flight Operation Crowflight from 1960 to 1966. Operation Crowflight utilized U.S. Air Force U-2 and RB-57 high-altitude aircraft to fly into the stratosphere to collect particles of fallout at high altitude. Initial theories that fallout would decay while suspended in the stratosphere proved inaccurate. Over time, the measurements from these flights demonstrated that the largest proportion of fallout returned to the troposphere within 5 degrees of 40 degrees N latitude (Dunning, 1960; Dorling, 2016). The values shown in Fig. 8 demonstrate global fallout distribution patterns from stratospheric contribution.

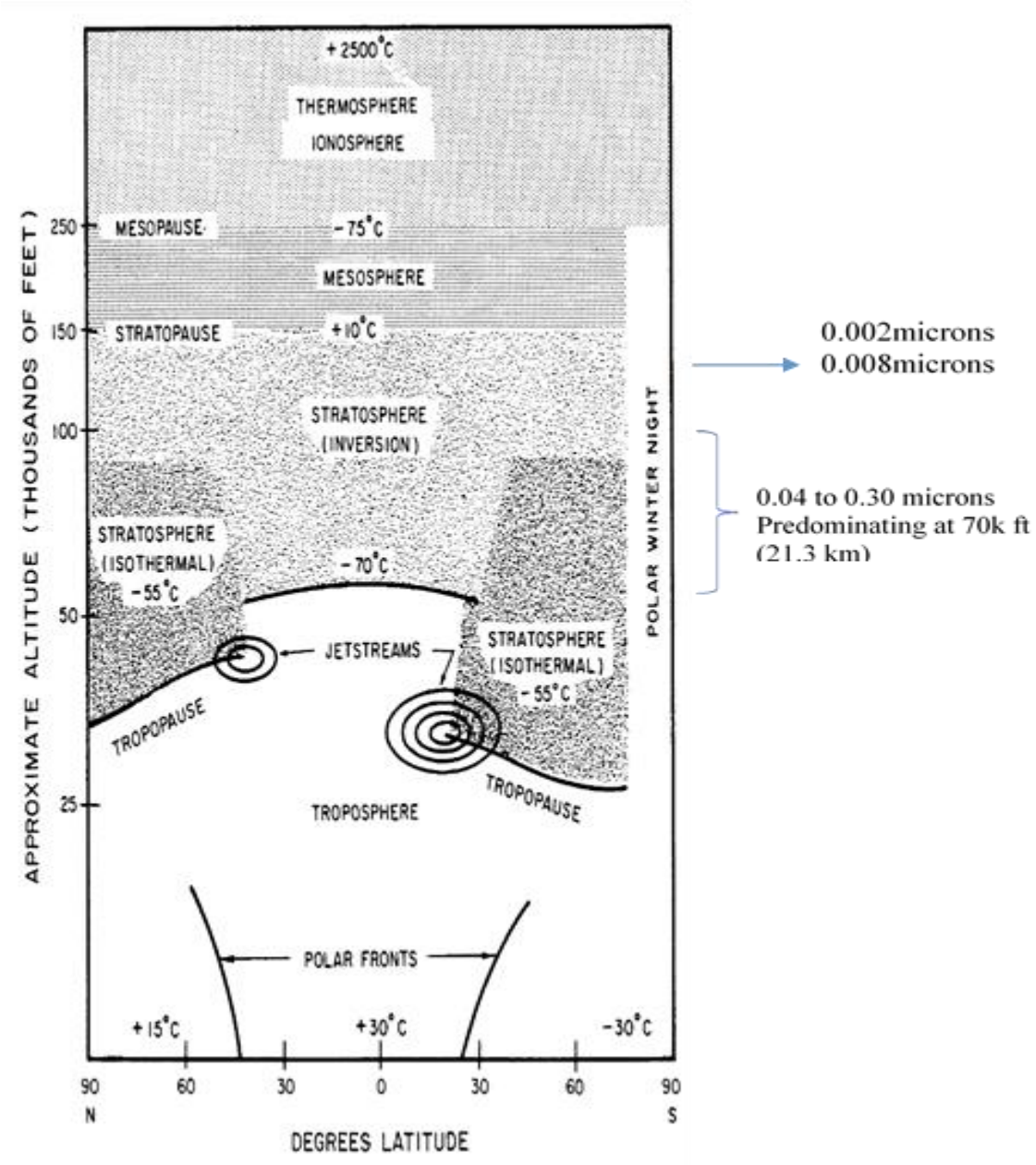
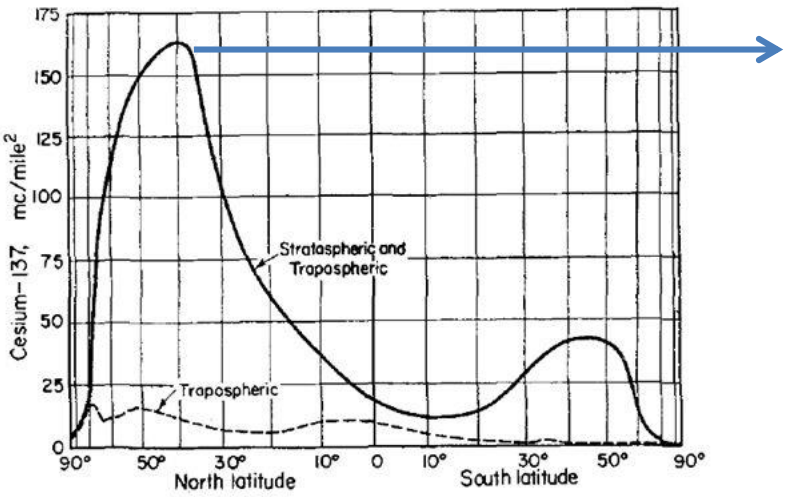


Figure 7. Behavior of fallout as a function of particle size and position in the atmosphere. Combined from Libby, 1959; Klement, 1965; Langham and Anderson, 1959).



The peak value translates to 2.3×10^6 Bq/m^2.

Figure 8. Values of overall fallout across the globe (Dunning, 1960).

Health Impacts from Fallout

Once scientists realized that smaller fallout particles remained aloft for long periods and returned to earth thousands of miles from the release site, studies developed regarding their impact on public health and the environment. The DOE tasked the Health and Safety Laboratory to identify and analyze fallout. Beck et al. (1990) placed large gummed paper sheets measuring several feet square in 150 locations around the United States to capture fallout for analysis (Fig. 9). The gummed sheets, similar to flypaper, in theory would capture fallout as dust, though in rain situations, the authors noted variations.

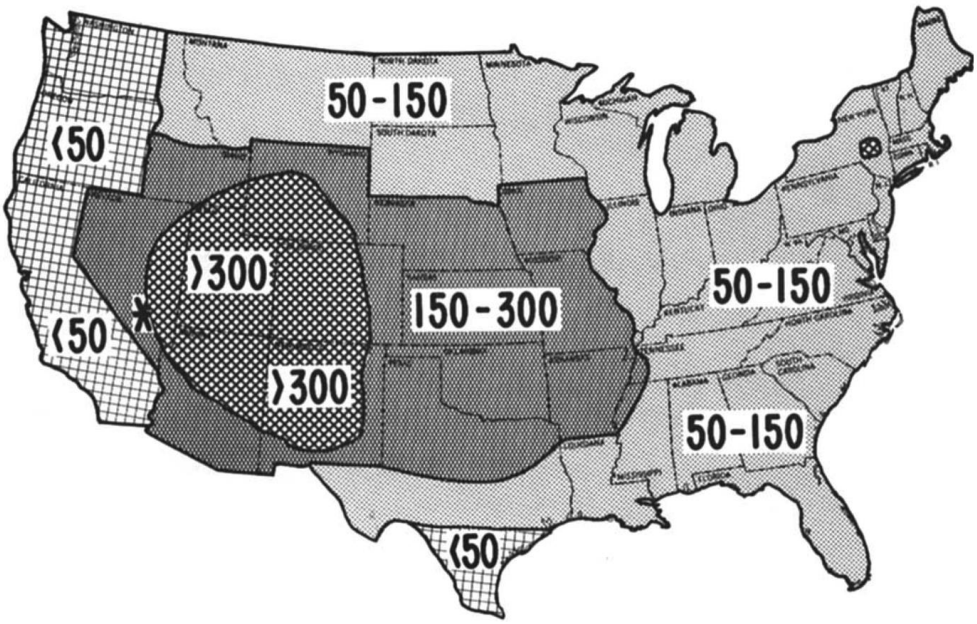


Figure 9. Approximation of radioactive fallout in Bq/m2 from the Nevada Test Site as generalized from 150 gummed film captures and analysis. (Beck et al., 1990)

The three major isotopes studied in the 1950s and 1960s included iodine-131, strontium-90, and Cs-137. All these isotopes pose long-term health impacts and therefore inspired significant scientific and public interest. Many nuclear release products decay in moments to hours or exist in relatively minor concentrations, while other isotopes such as Cs-137 and Sr-90 persist for long periods.

The chemical properties of I-131, Sr-90 and Cs-137 allow for incorporation and retention in the human body. Each isotope has a unique pathway, half-life, and duration of effect. Other than the impact of I-131 on the thyroid, most concern centers on whole body long-term dose equivalence.

Table 2. Characteristics of the three major isotopes of concern for human health

Isotope	Half-life	Organ(s) of interest	Reason for Interest
I-131	8.1 days	Thymus/thyroid	Thyroid cancer
Sr-90	22 yrs	Teeth and bones	Whole body exposure/cancer
Cs-137	30.1 yrs	Whole body	Whole body exposure/cancer

Iodine, released most often as a gas from a nuclear release, enters the body through inhalation or from incorporation into the food chain. As a halogen, iodine readily interacts with water. The use of non-radioactive potassium iodide (KI), which contains the stable form of iodine (I-127) was developed to counter possible uptake of iodine-131. Once the thyroid gland of humans and other mammals is saturated with iodine, the body will excrete any newly-ingested I-131. Strontium, as the Sr^{2+} ion, mimics the actions of calcium with emplacement into bone. Once ingested, Sr^{2+} can irradiate the body from within for years. Cesium, as the Cs^{+} ion, can mimic the actions of potassium, which the body uses in many physiological processes.

In 1999 the National Academy of Science (NAS) studied the possible correlation a person's age to I-131 dose from the atomic bomb testing era. The data imply that those who were young during the Nevada Test Site detonations have received a greater ingestion from this isotope. Since the half-life of iodine in the body is relatively brief due to physiological processes, these data show the relative speed at which iodine-131 acts on the body. Equation 2.0 demonstrates the calculation used. In the case of I-131, the effective half-life of 132 hours, or 5.5

days, demonstrates the importance of either removing populations from the fallout zone, or providing KI tablets to those sheltering nearby.

$$\text{Effective half life or } T_{1/2e} = \frac{T_{1/2p} \times T_{1/2b}}{T_{1/2p} + T_{1/2b}} \qquad (2.0)$$

Work by Eisenbud (1997) and the NAS (1999) show that younger persons have greater susceptibility for thyroid cancer as well as other thyroid afflictions, e.g., hypothyroidism, as adults. As research continued, more sensitive measurements and impact determinations became possible. In studies relating birth year to total body radiation it was found that uptake by young people occurs at different rates and with a different body burden (Table 3). Those born in 1952 accumulated more radiation in their youth, due in part to fallout exposure from the larger Mt detonations (Table 3).

Table 3: Date of birth correlated to accumulation of I-131 in the human body (NAS, 1999)

Birthdate	Reference dose (mGy)	Ratio of dose in birth year to dose for those born in 1952
Jan. 1. 1962	0.0001	0.000001
Jan. 1. 1957	85	0.71
Jan. 1. 1952	120	1.00
Jan. 1. 1947	64	0.53
Jan. 1. 1942	44	0.37
Jan. 1. 1937	25	0.21
Jan. 1. 1932	11	0.09

Divide by 10 to convert to rad.

The May 1966 Chinese atomic bomb test (250 kT) in the Pacific produced measurable fallout which on most of the United States. Through careful observation, the heaviest fallout occurred in Arkansas. During follow-up studies, the Pasteurized Milk Network detected I-131 in many states; data were compared to that from the respective State Public Health Agencies (Fig. 10). Figure 10 shows both locally reported values and those reported by the respective state board of health (in rectangles). The numbers represent picocuries of I-131 per liter of milk (Strong et al., 1970). The Indiana value of 190 pCi/l equals just over 7 Bq/l, a very low value.

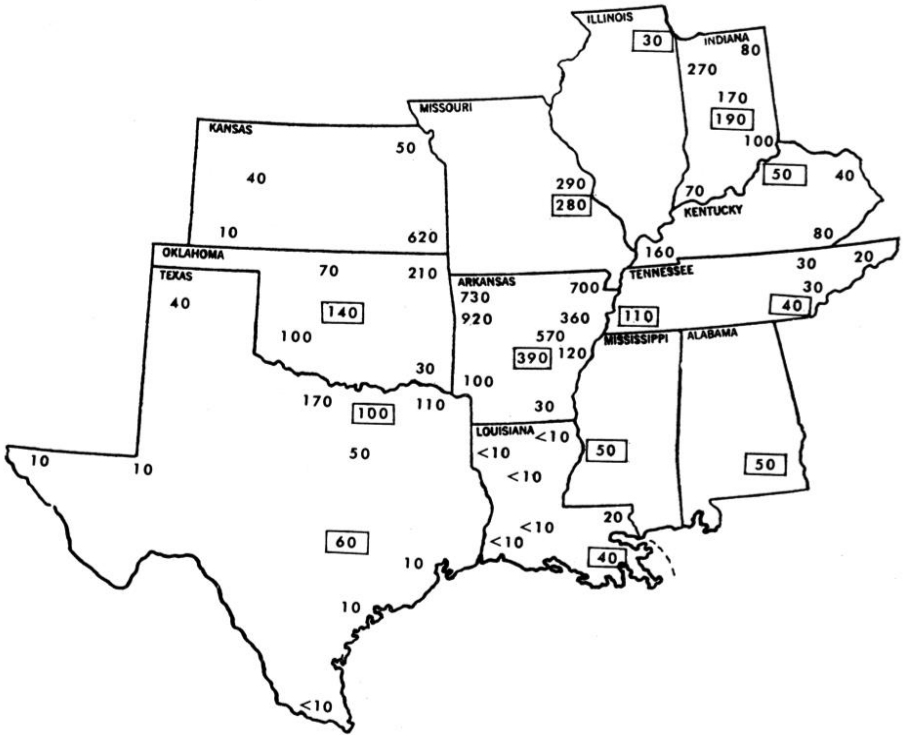


Figure 10. Iodine-131 data from the Pasteurized Milk Network tests, and values reported within respective states.

The Strong et al. (1970) study timed the duration of measurable fallout for I-131 and Sr-90 at about 2 weeks and 1 month, respectively. This work provides insight into the longest window during which dairy cattle, for example, might graze on forage contaminated by fallout.

Following the Fukushima reactor failure, both the Indiana State Board of Health and faculty at Ball State University captured samples on filter paper for analysis of possible fallout. The analysis (Fig. 11) shows that both locations measured I-131 (Ramirez-Dorronsoro, 2017). The values showed variation, demonstrating that fallout occurring in nearby areas will differ and that local weather plays a major role in deposition.

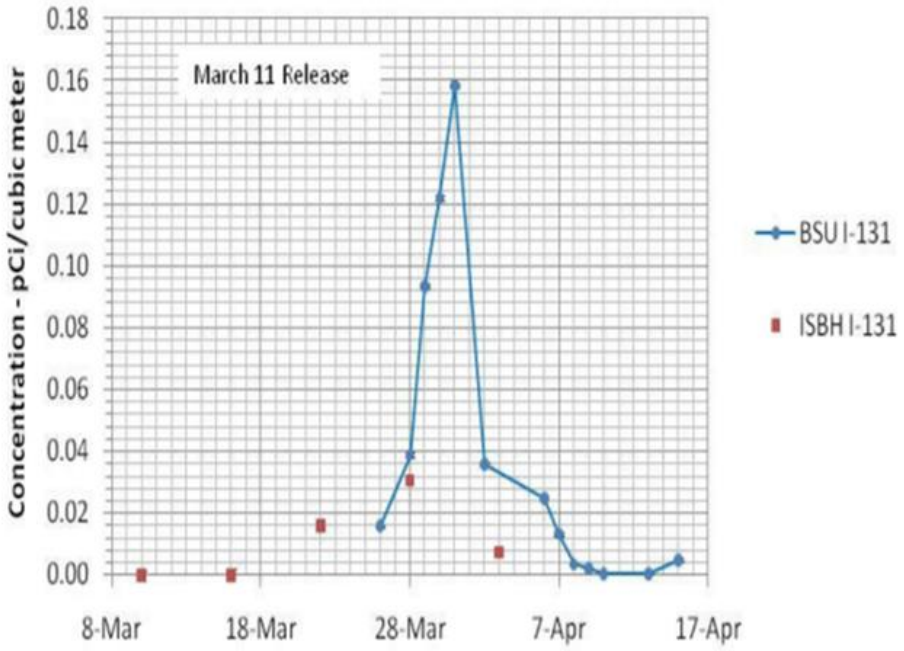


Figure 11.Iodine-131 activities in Muncie, IN, March 8 through April 17, 2011. (Ramirez-Doronsorro, 2017)

In studies at Waterloo, Ontario, Canada and at the University of Washington at St. Louis, MO, precise measurements of thousands of infant deciduous teeth determined values of Sr-90 from fallout. Table 4 shows how the uptake of Sr-90 increased during the atomic age (Mangano and Sherman, 1999).

Table 4: Results of studies in the United States and Canada regarding Sr-90 incorporation into teeth from ingestion, 1957 births, bottle-fed (Mangano, 1999).

Location	Sr-90 Concentration
	1.96
Toronto	
Michigan	2.47
Indianapolis and Chicago	2.77
St. Louis	2.79
East Texas and New Orleans	3.43
California	1.53
Average All Locations, Excluding St. Louis	2.43

As nuclear testing continued through the 1950s and 1960s, fallout capture techniques improved and many counties began to operate air samplers and conduct area radiation surveys at regular intervals. Iodine-131 had particular importance to many nations, due to the speed at which dairy cattle incorporate it into their milk. Iodine-131-contaminated milk was found to pose a thyroid hazard to growing children due to their metabolism and rapid update of this isotope (Mück, 1995).

Hull (1963) at Brookhaven National Laboratory produced the seminal work on the interaction of fallout with vegetation during the summer and fall of 1962, and from there into milk. By this time, Brookhaven National Laboratory could measure radiation in units as low as 'micro-micro' Curies of iodine-131. Today, the term picoCuries or 10^{-12} Curies substitutes for the micro-micro unit. Several scientists documented pathways from forage through cattle thyroid glands and into human populations (Bustad et al., 1963).

In work by Mangano (1999) (Table 4), the Sr-90 measurement per gram of tooth enamel provides information on ingestion by birth year. In a second study, the highest rates of cancer followed the Chernobyl reactor failure (Mangano et al., 2000) (Table 5).

Table 5: Comparison of birth year with uptake of Sr-90 and cancer incidence in children

Birth period (teeth)	Diagnosis period (cancer)	High pCi Sr-90/g Ca	Ave. pCi Sr-90/g Ca	Cancer incidence* Ages 0-4 y
1979-1981	1982-1984	3.45	1.11 (11)+	17.40 (46) ±
1982-1984	1985-1987	2.60	1.26 (23)+	20.17 (55) ±
1985-1987	1988-1990	7.26	1.50 (70)+	25.52 (73) ±
1988-1990	1991-1993	7.86	1.45 (110)+	19.29 (58) ±

Notes: Sr-90 = strontium-90, and pCi Sr-90/g Ca = picocuries strontium-90 per gram calcium.
+Numbers of teeth analyzed in parentheses.
±Numbers of cancer cases in parentheses.

The third isotope of concern, Cs-137, also raised concerns in the public health arena because its long half-life could result in a long-term cumulative whole body exposures and might lead to cancer. In 1990, the National Cancer Institute published maps showing exposures resulting from fallout. Figure 12 shows deposition by county of fallout until 1997. This map shows deposition from the Chernobyl disaster but not the smaller Fukushima reactor failure. The higher fallout values in the mountainous areas of New England indicate likely interaction with fallout clouds or from local rainfall.

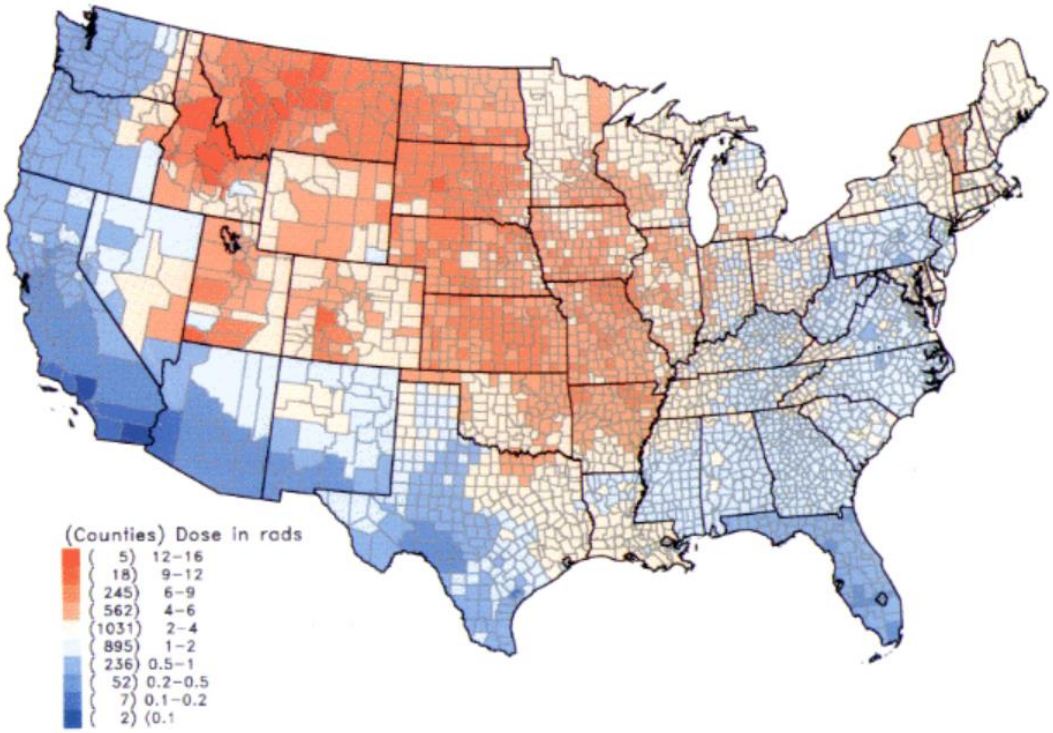


Figure 12. U.S. National Cancer Institute map showing the accumulated radiation exposure by county in the continental United States (1997); these equate to REM (or divide by 100 for Sv equivalent).

In 2010, the U.S. Centers for Disease Control (CDC) published data regarding fallout deposition, including Cs-137, on the United States during the 1960s (Fig.13). The magnitude of deposition, in 10^{14} Becquerels, likely spread based on factors including local winds and precipitation rate. Differences in precipitation alone will create variations in deposition to the surface.

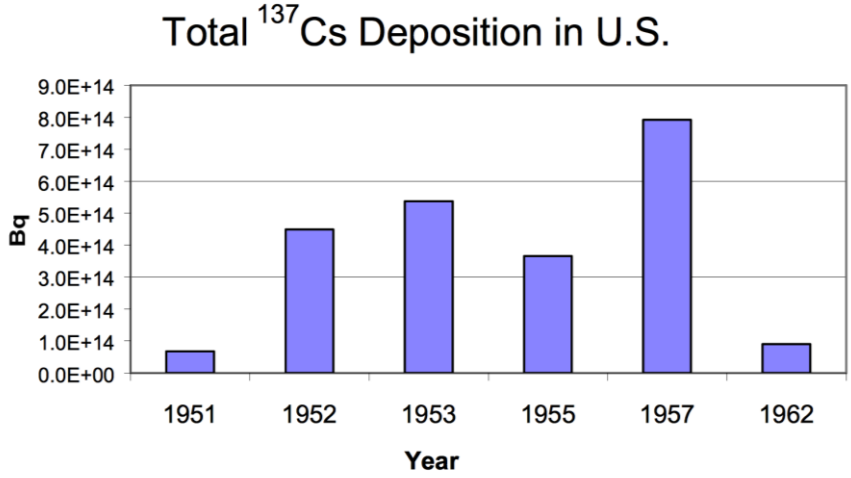


Figure 13. Deposition of Cs-137 by year on the continental United States, 1951-62 (CDC.gov)

The CDC compiled several maps showing fallout from the Nevada Tests and from other releases, over Asia and the Pacific Ocean by Russia, China, France, and England. Figure 14 shows fallout per square meter across the U.S., with most of Indiana having received radiation in the 100 to 300 Bq, and a few locations with 300-1000 Bq. Figure 15 demonstrates total fallout from all global tests and fallout from the Chernobyl disaster. Figures 14 and 15 demonstrate substantially greater deposition from tests located far from the United States rather than just from the Nevada Test Site. This effect resulted from jet stream transport of fallout from the many megaton weapon injections of this material into the stratosphere. These maps contain greater detail than shown in the figure 9 map by Beck et al. (1990).

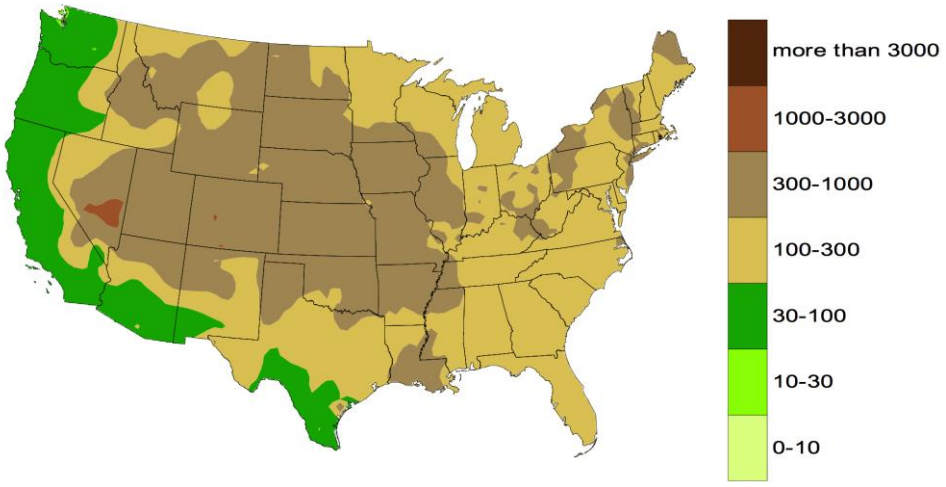


Figure 14. Areal deposition of Cs-137 in Bq/m2 across the continental U.S.(CDC.gov, 2010).

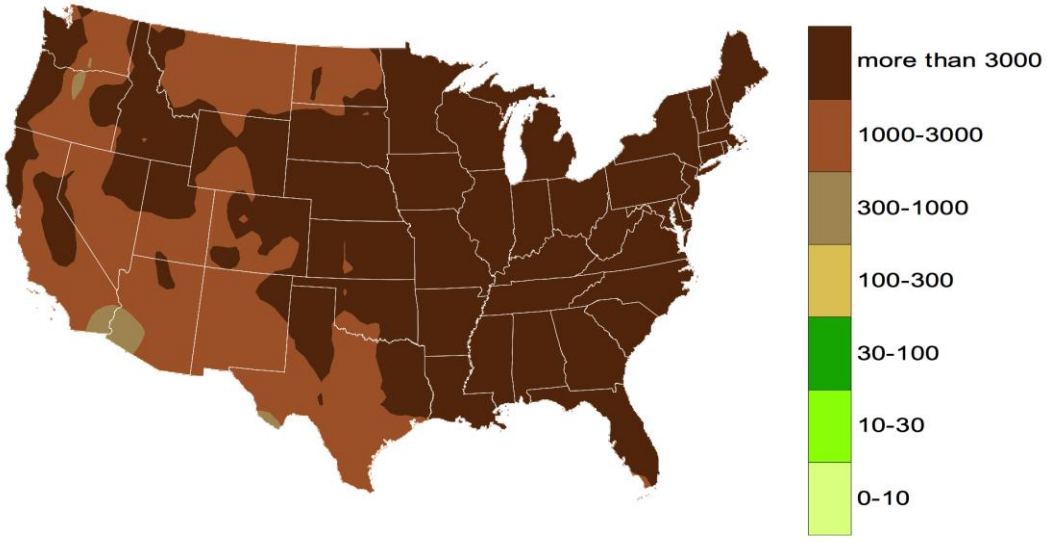


Figure 15.Deposition of all global fallout of Cs-137 (CDC.gov, 2010)

Fig. 15 shows deposition from all nuclear weapons tests and the Chernobyl reactor failure. Compare to Fig. 10. The entire eastern half of the United States received higher values than from just the Nevada Test site as shown in Fig. 14.

The Sedan Test was an announced demonstration of an underground detonation (104 kT) in July 1962. Its purpose was to demonstrate the capability to construct an underground bay or canal as part of the 'Atoms for Peace' program of the Eisenhower administration. This last U.S. test produced significant fallout measured by many counties in the United States (Krige, 2006).

Ritchie remained involved through the 1970s and 1980s and with others produced eighteen major studies addressing soil organic matter and sediment, most using measures of Cs-137. These studies used Cs-137 because by the 1970s I-131 had decayed and Sr-90 presents greater difficulties in measurement.

Chernobyl and Fukushima Reactor Failures

Soil studies diminished through the latter 1970s and into the 1980s as nuclear testing had ceased. The Chernobyl reactor release of 1986 renewed interest, as this single large release which continued for about 12 days, allowed for extensive measurements. Shand et al. (2013) measured the presence and migration of Cs-137 in the soil, grasses and sheep meat of Scotland.
In Greece, a 10-year retrospective study of the Chernobyl fallout by Kritidis and Florou (2000) (personal communication with Kritidis, September 2013) captured the details of fallout arrival and then followed it in soil, surface waters, marine environments, to food and even into the Greek population. Using International Commission for Radiation Protection standards, it was determined that although 350 additional cancer deaths over the next 50 years might result, the

authors state that this number is “insignificant” when compared to the Greek population size and natural cancer rate.

One decades-long duration project (Beresford, 2016) studied the concentration of Cs-137 from lichens to meat, and then into humans in Sweden. The uptake by those eating reindeer meat provides an indirect history of radiation releases (Fig. 16). This work also illustrates that lack of rainfall at higher latitudes where snow predominates fallout may persist on the soil surface rather than migrating into the soil, especially on lichen type vegetation. Note the decline after most large nuclear weapons testing ended in the 1960s and the rapid rise following the 1986 Chernobyl release.

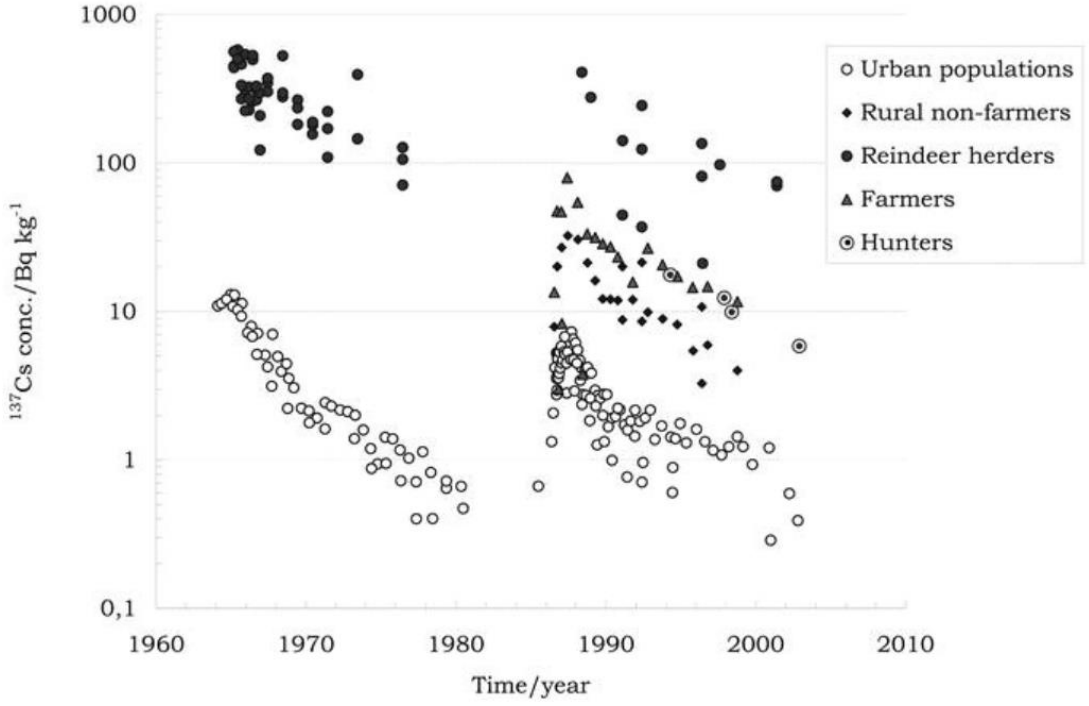


Figure 16. Median whole-body concentrations of Cs-137 in five categories of the Swedish population.as evaluated by Raaf et al. (2006).

Nuclear weapons and commercial nuclear power reactors have several similarities and notable differences as regards behavior of isotopes during a release (Zheng et al. 2005). Among the similarities, the types of isotopes, e.g., I-131, Sr-90, and Cs-137 all appear following a release; however, a nuclear power plant can release more of all types due to the quantity of uranium fuel present and the duration of a failure and containment breach. Both Chernobyl and Fukushima produced far greater initial releases of I-131 than did the much smaller but contained reactor incidents at Three Mile Island (PA) in 1979 and at Windscale in Cambria, England in 1957 (Loutit et al., 1960).

One dramatic difference between a reactor failure and a weapon detonation involves the magnitude of the release: the Chernobyl steam explosion carried radiation into the troposphere, but it also continued to vent for many days. The reactor design did not include the modern containment system that would have retained much of the radioactive steam. The Fukushima event, while not as powerful as Chernobyl, resulted in essentially the same release as at Chernobyl and also lasted about 12 days; however, without the steam explosion, this incident did not disperse as much high-altitude fallout as seen at Chernobyl. A large portion of radiation from the Japanese event involved direct infiltration to the ocean although several small hydrogen gas explosions produced locally elevated fallout levels (Estournel et al., 2012; Thielen, 2012). Dr. John Cardarelli, a U.S. Public Health Service Captain working within the U.S. EPA, took part in the Fukushima response and measured similar variations in I-131 levels around Narita, Japan in the week following the reactor loss. The prompt use of KI by the Japanese government likely limited thyroid exposure (Cardarelli, personal communication, 2013).

Recent work by Semenkov and Yu (2015) with ArcGIS software allowed for determination of the long-term fate and deposition patterns of Cs-137 in a watershed in Russia. Beebe (1986) wrote a history of fallout on agriculture from 1970-1986, and Zhang (2015) stated that latitude, climate and other characteristics will influence deposition and retention of Cs-137 and included vegetation type as an additional factor, i.e., where and how much Cs-137 is deposited in the plant. This kind of work has made phytoremediation as a possible removal strategy in other areas (Dominguez-Rosado and Pichtel, 2004) but has had only limited application with Cs due to it relatively poor uptake.

Following the Chernobyl and Fukushima events, soil profiles worldwide were analyzed for Cs-137 and patterns emerged as to the location of Cs-137, Sr-90, and lead-210, all having long half-lives and with the ability to contaminate normal biosphere pathways. Analyses of soil produced some interesting similarities in profiles regardless of soil type; for example, Cs rarely penetrates below 15 cm and nearly always accumulates to within the top 10 cm of the profile (Shand et al., 2013).

Several recent studies have determined that the northern hemisphere would receive much more fallout than the southern hemisphere, except in the case of the higher yield weapons (measured in megatons), which carry material into the stratosphere and then cross the equator (Elmar, 1963; Makakov,1970; Machta, 1962). Current data, especially from the Chernobyl reactor release, have provided significant information on the fate of fallout in the troposphere, especially since the reactor core continued venting for nearly two weeks. Fallout information was captured by many nations from this event, including Finland (Jantunen et al., 1991), Germany (Bunzl et al., 1989; 1990), over the northern Pacific Ocean (Buessler, 1996) and at the Naval Surface Warfare Center, White Oak Laboratory (MD).

Significant work by many has provided insight into micron and sub-micron behavior of fallout in the troposphere and stratosphere. Mamura et al. (1963) initiated studies of particle size of fallout. Imanaka et al (2005) retraced the probable plume of the first Soviet (1949) nuclear test and compared this data with that of fallout in soil samples on its pathway. Others have examined size, shape, and aerodynamics of high-altitude fallout (Mamuro et al., 1967; Hardin et al., 1964; UNSCEAR, 2000). In 2012 Paulson et al. developed a mathematical model to predict fallout deposition at different latitudes.

Other scientists have studied fallout accumulation in rivers, streams and lakes (Walling et al., 1999). Robbins and Eddington (1974; 1975) tested the depths of Lake Michigan to determine a settling rate of fallout at 0.28 centimeters per year, implying that return from the atmosphere occurs at that rate.

Behavior of Fallout Isotopes in the Biosphere

Over time, a greater understanding of the various pathways of fallout in the biosphere has evolved (Fig. 17). In this model soil, animals, plants and water bodies and sediment act as receptors for isotopes. As stated earlier, Cs-137 will behave in a manner similar to potassium.

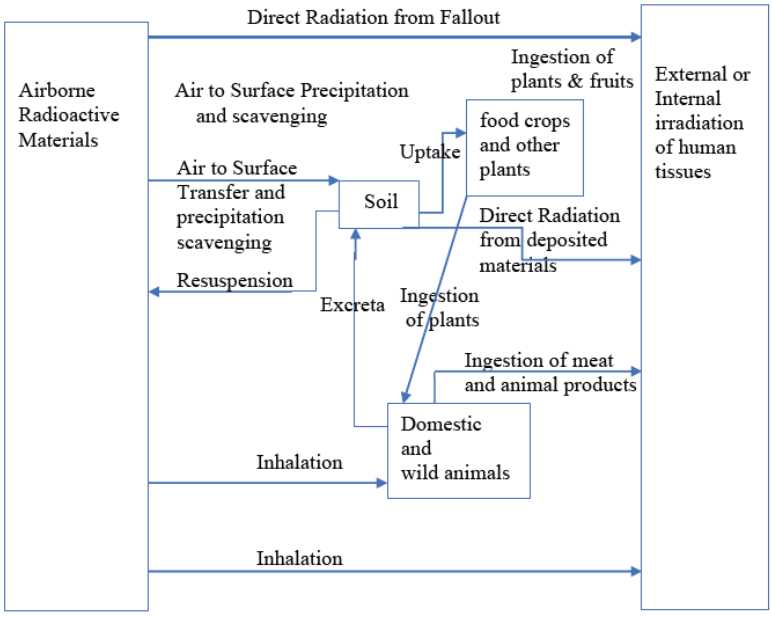


Figure 17. Potential pathways for radioisotopes in the atmosphere, geosphere and
Redrawn from Langham and Anderson (1959).

Components of fallout can be taken up by lichens (Ellis and Smith, 1987), in mushrooms (Horyna and Zanda, 1988), and in rice (Leung and Shang, 2003). Shand (personal communication, January 28, 2013) found low uptake of Cs-137 in plants and very low uptake in sheep meat in Scotland. He concluded that after the first rainfall, virtually no Cs-137 remained above ground. Furthermore, once the isotope had reached 5 cm below ground it would not interact with plants due to the binding action with clay (Shand et al., 2013; Chaplow et al., 2015). He and Walling (1995) found a relationship between size of fallout particles and size of soil particles to which these would bind. Studies in undisturbed grasslands of Bavaria by Schimmack and Schultz (2006) compared soils to a depth of 80 cm and found the mean depth of Cs-137 to be 5.6 cm. Weesner and Fairchild (2008) sampled soils in five regions of Nebraska and found peak activity at or above 10 cm. An Ohio study by Bajracharya et al. (1998) showed little Cs-137

present below 15 cm. In forest studies, Winkelbauer et al. (2012) reported that very little Cs-137 penetrated below 10 cm of the Bavarian forest floor. Konoplev et al. (1993) found that following the Chernobyl release, all of the fallout was bound to the soil within 10 days.

While many scientists expressed concerns over the potential medical implications of fallout, other groups found isotopic fallout useful in new ways. In England, Cambray et al. (1976) continued monitoring air and rain through the 1960s until the end of 1975, noting peak fallout in 1963-1964. By 1985 this organization could no longer detect fallout (Ritchie and McHenry 1990). In the 1970s soil scientists noted that the Cs-137 from fallout in soil had utility to examine erosion as part of the development of refined Universal Soil Loss Equations (Bajracharya et al., 1997). Menzel (1960) compiled data in Georgia and Wisconsin soils, and Frere and Roberts (1963) measured I-131 and Sr-90 in Ohio soil. Rogowski and Tamura (1965; 1970) applied Cs-137 to turf plots in Tennessee to study soil erosion. Wischmeir and Smith (1978) combined their work with the above groups and found a 0.94 correlation across the different measurements of soil loss.

Ritchie et al. (1970) used Cs-137 as an indicator of deposition in Georgia valleys from erosion and in 1990 measured erosion in other kinds of terrain. Other studies followed, including work in Saskatchewan by Jong et al. (1982), in Georgia (USA) by Ritchie et al. (1990), in Norwich, England by Walling et al. (1999), and in Ohio by Matisloff (2002). A number of studies on rate of deposition of fallout into Lake Michigan by Plato (1972) and Plato et al. (1975) allowed for correlation of sediment deposition rates to nuclear detonations to 0.28 centimeters per year and to earlier atmospheric residence predictions by Dunning (1960). This data helped determine atmospheric residence times of fallout.

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CHAPTER 3: EXPERIMENTAL METHODS

Site Selection for Soil Sampling

This study involved soil sampling from all 92 Indiana counties in order to create a county-by-county statewide census of the presence of Cs-137. Prospective sampling locations included both forested areas (predating 1940), and sites in permanent grassland/turf (also predating 1940). All sampling sites were required to be on locally level terrain. A ratio of 2:1 forest to grassland sampling sites across the state was considered appropriate for to attain statistical reliability. In the end, a total of 67 forest and 25 grassland locations were made available for sampling. Four control sites, i.e., where soil was presumably not in contact with fallout, were also selected.

A number of sampling locations were provided by those willing to volunteer their property for sampling, and state and federal agencies. In addition, Elizabeth Jackson of Purdue University emailed a request to the Indiana Forestry & Woodland Owners Association, requesting permission to sample soil on their property with the link to a 50-second YouTube video [https://youtu.be/1PfJZ0uChqM.]

The letter shown in Fig. 19 accompanied all requests.

Figure 18. Screen captures from video provided to landowners.

Dear _____,

Please view this short 50-second video at https://youtu.be/1PfJZ0uChqM to see what kind of sampling I need to do on your property this summer. The process takes less than 10 minutes and I hope you can support this effort.

I will log the sampled site with latitude/longitude to show my adviser that I visited each location, but the doctoral dissertation will only show the locations by county as the project involves a kind of generalized soil census across the whole state against rainfall, the amount of clay in the soil, the land elevation, and the types of trees (as most samples need to come from older forested areas as these have less erosion). About 1/3rd of my samples need to be collected from either permanent grassland, lawns, etc. that also have not been plowed since 1940. Mowed grasslands will work.

You can call my cell or email me at rtwhitman@bsu.edu with questions.

Best Regards,
Rick Whitman
Doctoral Candidate, Ball State University
(317) 847-4178

Figure 19.Request for soil sampling via email.

After the Indiana Forestry & Woodland Owners Association was contacted, 40 forest owners and 10 grassland owners responded within three hours. Indiana colleges and universities all agreed to allow sampling as well, as did some county fairgrounds and city parks. The Indiana Division of Nature Preserves granted permission to sample on four properties under conditions in an issued permit and that they would receive any results in writing. Eventually, more than 70 locations became available from the above request process or by referral. To complete the sampling, ‘on the spot’ requests while traveling proved successful. Offers by private landowners to allow sampling often came with the condition that the product would not include the owner's address.

Sampling Location Requirements

For forest sampling locations the desired sites required the following characteristics:
trees must have been present since 1940; non-marshy surface, preferably non-flooding; near-level surface with a minimum size of 200 by 200 ft (60 x 60 m). For grassland sites, the location must be unplowed, level and non-flooding and measure at least 100 by 100 ft (30m x 30 m). Four control samples collected from crawl spaces under older homes and from under a barn slab. These samples were expected to have had no direct contact with atmospheric fallout.

Sample Collection, Preparation and Analysis

At each site, an AMS® Slide Hammer (Figs. 20) was used to remove soil of consistent volume to fill a 1-liter Marinelli Beaker (Fig. 22). The AMS slide hammer allows the removal of an intact cylinder of soil. Sampling involved collection of two samples at a single location in each county; samples were collected from within 1 m of each other,

Figure 20.AMS slide hammer (left) and sample extraction (right).

Area of cylinder = πr^2

3.14 (14.51) = 45.56 cm^2 each or 91.12 cm^2 for both cylinders

(multiply by 1.09 to convert to 100 cm^2)

Sample depth from extracted soil was 12 cm (depth) – 2 cm (surface) = 10 cm core

Typical volume = πr^2 x h (presuming no roots or rocks) for a mass of about 1 kilograms each.

3.14 x (0.5 x 7.62) x 10 cm = X cm^3

3.14 x $(3.81)^2$ x 10 cm

3.14 x 14.51 x 10 cm= 455.61 cm^3

Two samples at each site were necessary to fill the 1.0 liter Marinelli beakers to the 0.75 liter mark or greater to provide consistent readings.

Figure 21. AMS slide hammer calculations.

The sample (inner) slide hammer cylinder measures ~3 inches (7.62 cm) diameter and 9 inches (22.86 cm) height. After sampling, the inner cylinder was removed, excess soil was trimmed using a marked cutting board and knife from a depth of 2 cm from the surface to a depth of 12 cm. Each sample was placed in a Ziploc® bag. Local information, including site GPS coordinates were recorded. The surface to 2 cm increment was removed as it was unlikely to contain Cs-137 and would therefore only dilute the measurements.

Soil samples were transported to the Natural Resources and Environmental Management Soil Laboratory at Ball State University. Soil material was oven-dried at 99º F (40ºC) for 24 hours in foil pans. The dried soil was ground using an agate mortar and pestle and then sieved to through a 2-mm mesh sieve. Sieved soil was then placed into the 1-liter Marinelli beakers (Figure 22) as recommended by Dr. Jim Schweitzer, the Purdue University Radiation and Environmental Safety Officer. After filling, each beaker was sealed with electrical tape to the lid edge to prevent samples from absorbing moisture from the air. The net mass of the sample was measured.

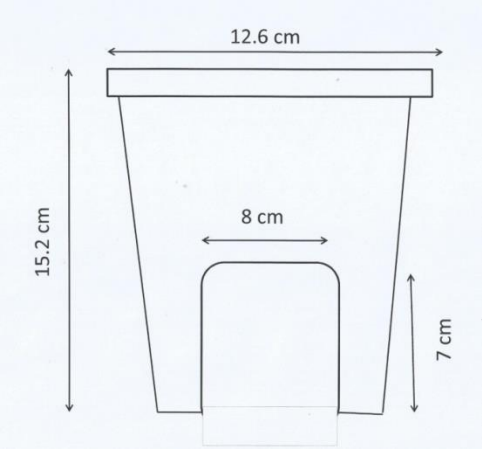

Figure 22. Side view of 1-liter Marinelli Beaker

The relative quantity of clay in each sample was estimated using the texture-by-feel method. Scores ranged from 1 (low) to high (5). Soil samples were also assigned a hue, value and chroma from Munsell charts (Munsell Soil Color Book, 2009), X-rite Pantone, Grand Rapids, MI). Soil pH was determined for each sample using a 1:5 ratio of soil:water and a Fisher Scientific Accumet pH meter. The use of a pH buffer between readings ensured accuracy and verification of the meter performance.

Soil samples were delivered to the Purdue Radiation Laboratory at West Lafayette, IN for analysis on an ORTEC Germaninum-Lithium detector cooled by liquid N_2. Each sample was counted for the presence of radioactive material for two hours after daily instrument checks. It has been determined that one-hour counts on this instrument will provide 95% accuracy (Schlein, 2002). Each sample was encoded to ensure that laboratory staff did not know the sampling location (Byrnes, et al., 1994)

ORTEC GammaVision® software measured the presence of the three isotopes (Cs137, Pb-210, and K-40) in Becquerels. The software determines identities based on the energy signatures of many isotopes. For the current study, Cs-137, Pb-210 and K-40 were studied. Figure 23 demonstrates the spectrum from a single sample; in this case, Cs-137 had a value of 64 counts (Bq). Other peaks in the software correspond to other and mostly naturally occurring long-lived isotopes.

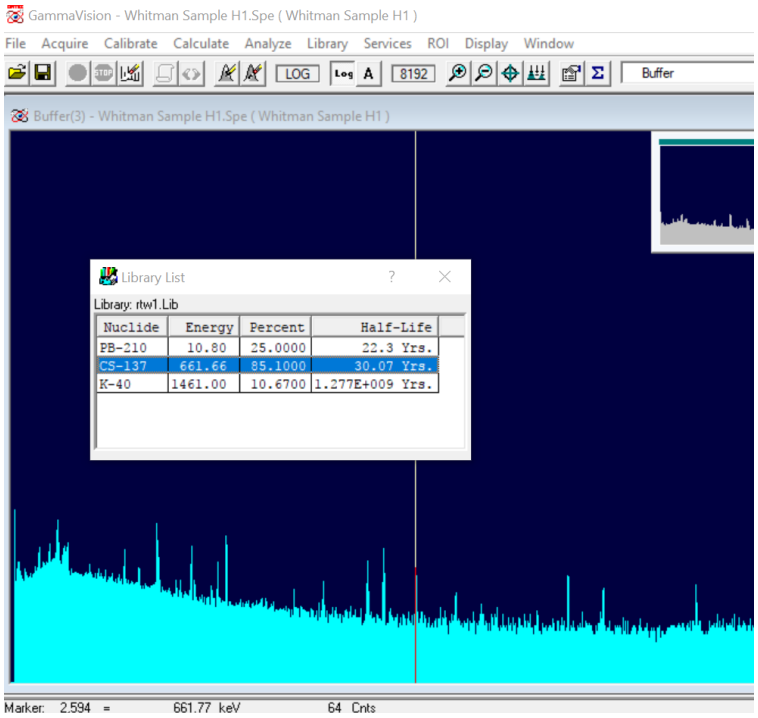

Figure 23. Gamma Vision Software showing peak identification and reading for a sample.

Statistical Analysis

After determination of the presence of Cs-137, Pb-210, and K-40 activity in the soil samples, results were compared to rainfall and clay content using SPSS24™ on a Windows-based PC. Initial tests included both Levene's test and the Kruskall-Wallis test to ensure homogeneity of variance condition, which both tests supported. Descriptives and Means Testing subsequently confirmed the significantly greater retention of Cs-137 in the forested areas compared to the grassland areas. The SPSS histogram plots of the Cs-137 in both areas against a normal distribution curve provided a visual confirmation of the difference between the two groups. Other tests compared all combinations of precipitation, clay and forest and grassland, and the activities of other isotopes (Pb-210 and K-40). Both pH and Munsell color comparisons proved difficult to compare; neither had consistency across the state.

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CHAPTER 4: RESULTS AND DISCUSSION

Units of Measurement in this Study

Samples presented in this work have been expressed in two units; the first shows the activity of the original soil sample in Becquerels (Bq). The more relevant unit involves presenting Cs-137 activity to area sampled, i.e., Bq/m^2 , which is the technique used in health physics soil studies

Since the samples in this work represent 91% of a 100 cm^2 soil area, they required adjustment by 9% to represent 100 cm^2 before extension to 1 m^2 for presentation as Bq/m^2 for comparison to published data. The activities of all values cited in the literature were adjusted to account for decay to July 1, 2017 for comparison. Other units, common before 1988, such as $milliCuries/mi^2$ were first converted to Systeme Internationale and then adjusted to represent decay to the present time.

Presence of Cesium-137 in Indiana Soils

Cesium-137 was detected in soils samples across all 92 Indiana counties (Table 6 and Fig. 24). Statewide, Cs-137 activities ranged from 654 to 24,634 Bq/m^2. The county markings as forest or grassland indicate the land type at the sample site and do not imply the land cover of the entire county.

The forest group (n = 65) had a mean Cs-137 activity of 8,730 Bq/m^2 and the grassland group (n = 27) had a mean value of 4,594 Bq/m^2. The latter value is 47.8% lower than that for forest soils. In the forest sites, Cs-137 activity ranged from 654 to 24,634 Bq/m^2. In contrast, Cs-137 activity ranged from 654 to 11,227 Bq/m^2 in grassland soils (Table 1 and Fig. 24).

Table 6: Cesium-137 activities in forest and grassland soils

	Forest	Grassland
Range, Bq/m^2	654-24,634	654-11,227
Mean, Bq/m^2	8730	4640
n	67	25

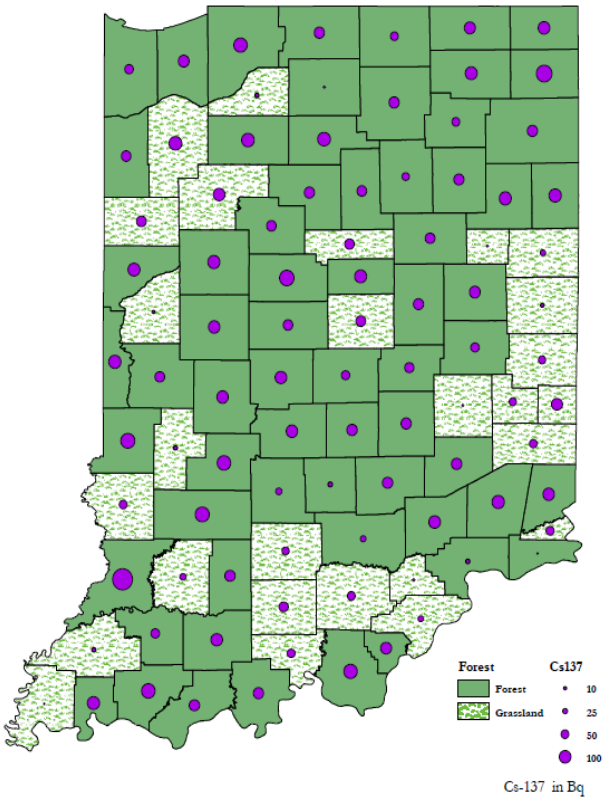

Figure 24. Activities of Cs-137 in 92 Indiana counties showing vegetation type

The most frequently observed Cs-137 activity was in the range of 7,500-8,500 Bq/m^2 (Fig. 25). The next highest frequency was from 9,600-10,500 Bq/m^2. One outlier value read 22,400 Bq/m^2. Generally, the tested forested areas showed a greater presence of cesium-137 per square meter than the grassland tested locations.

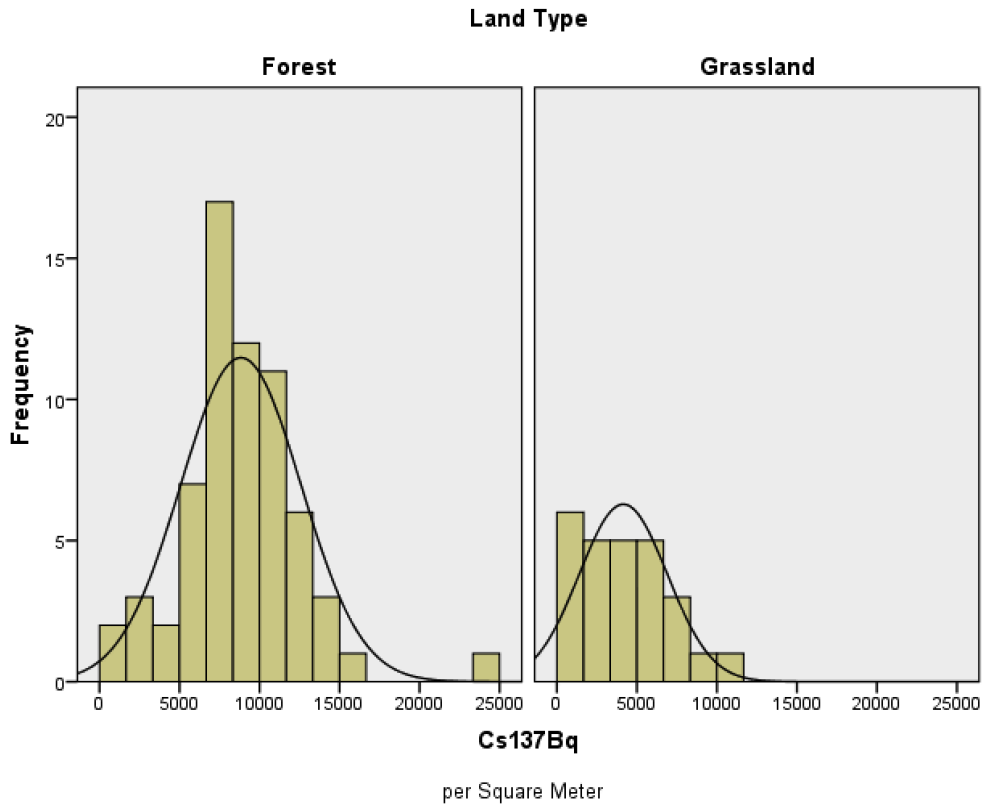

Figure 25. Histogram showing range of Cs-137 activity from 92 Indiana counties.

In the grassland soils, Cs-137 activity occurred predominantly in the ranges 600-8,000 Bq/m^2 (Fig. 25). Grasslands sometimes pose difficulties in comparison interpretation of fallout data, as most studies have involved sloping ground, where disturbance by plowing changes the Cs-137 content by promoting erosion. The Shand (2012) research in Scotland after the Chernobyl event concluded that Cs-137, when deposited on higher pastures, eventually migrated

below 5 cm depth and therefore experienced little uptake by grass. He also found that Cs-137 had bound to soil between the 5 and 10 cm depth. Cesium occurs as the +1 cation in the environment, and is expected to sorb to both soil clay and organic matter (Bostick et al., 2002).

Table 7 compares the ratio of Cs-137 in forest to grassland soils in the current study with the literature; as in all the reported studies, greater retention of fallout occurred in forests as compared with grassland. The value in Indiana is higher than those in Europe due to several factors, including the mixed fusion and fission releases from the 200 or more fallout depositions in the state plus a small addition from the Chernobyl and Fukushima reactor failures. Since the majority of the fallout within the Germany Cs-137 studies resulted mostly from Chernobyl and some from French low-yield and fission-only nuclear weapons tests in North Africa, a direct comparison would likely show differences as seen.

Table 7: Comparison of Cs-137 inventory in paired undisturbed forest and grassland locations

Reference	Location	Forest to Grassland Cs-137 ratio
Current study (2017)	Indiana, USA	2.02 : 1.00
Kuhn et al. (1984)	Hanover, Germany	1:65 : 1.00
Bunzl and Kracke (1988)	Bavaria, Germany	1.28 : 1.00
Bunzl et al. (1989)	Munich, Germany	1.20 : 1.00

Cesium-137 was detected in the Indiana control samples, albeit in minute quantities (Table 8). The size of fallout particles may explain this finding. Schlein et al. (1965) found that 88 percent of radionuclides more than 440 days old had a particle size of less than 1.75 microns. Glasstone (1957) noted the size of Cs-137 particles to be as small at 75 microns; he also noted that fallout of 75 to 150 microns contained as much as 18% of the deposited energy in fallout.

Control samples in the current study were collected from covered areas unlikely to receive direct or rainfall deposition. Three of the four were collected from crawl spaces in older homes or buildings and the fourth from under a large covered space with a soil floor at a county fairground. A measure from inside an English school showed values nearly as large as those measured outdoors in that area following the Chernobyl event.

Table 8: Cesium-137 values for control spaces, with adjusted results from England for comparison.

	Control 1	Control 2	Control 3	Control 4	England School 1992
	---------- Bq/m^2 ----------				
Cs-137	1,308	981	1,308	763	1,460

The data in Table 8 imply that extremely fine particles may present a unique hazard, as they could even penetrate Civil Defense shelters via normal air exchange. This information exceeded expectations.

Early determinations of fallout on the United States had significant limitations in terms of the measurement techniques available. Eventually, Beck et al. (1990), who performed many of

the measurements, published the estimated fallout from the Nevada Tests over the continental United States in 1963 from an original 89 sampled locations, later expanded to 150 gummed paper sites. These focused on the Nevada tests before analyzing data from the tests by other nations after 1962 and continued into the 1990s

In May 1987 the U.S. DOE Dose Assessment Advisory Group (Alpen, 1987) published a final report on contamination over the continental United States from tests performed by the United States. Table 3 provides information from the DOE report; with the data adjusted to show decay to the present, and converted to metric units. This study included 24 sites, from Seattle to Long Beach, CA, and eastward to St Louis, MO and Memphis, TN (but no farther east). Table 9 lists the tested locations closest to Indiana and also includes a value from France (LeRoux et al., 2014).

The high activity values in the current study likely arise from later fallout from tests conducted in the Pacific by the French, Chinese, Russians, and British. These occurred after the U.S. ended atmospheric tests in 1962. When adjusted to current activity of Cs-137, the data fits within the testing sequence before the conclusion of the Nevada tests had and before other nations tested significant megaton-yield weapons in the Pacific regions or Asia. The high value in Austria might result from the accumulation of different fallout events including Chernobyl-influenced fallout. Different types of atomic weapons over the years have produced different quantities of Cs-137.

Table 9: Comparison of adjusted Cs-137 data from the current study to other sites

Location	Cs-137 activity Bq/m^2
Indiana (current study)	10,218 (average)
France (LeRoux, 2014)	8,356 (high: typical 3,000 to 6,000)
Austria (Bossew), 2001)	15,840 (mean value in Austria)
Kendall, Arizona (Ritchie, 2009)	3,950
St. Louis, MO (AEC) 1984[#]	1,370
Memphis, TN (AEC) 1984	1,360
Dallas. TX (AEC) 1984	1,020
Indiana (1961)	463
Indiana (1961*)	5,636*
Canada (1980)	2,342 (high: typical 500 to 1800)

[#]From the US tests from 1952 through 1962.
*When adjusted by 12.71 suggested by Beckand Bennett (2002).

The study in France (LeRoux et al., 2014) at 42^o and 43^o N. latitude provide a strong comparison to Indiana data. The Canadian Northwest Territory study (Thomas et al., 1980) shows deposition but at lower values than those in the eastern United States due to its more northerly latitude. France received extensive fallout from the extended 12-day release from the Chernobyl disaster, whereas Indiana and the eastern U.S. received fallout from Nevada and the Pacific until 1980 when most testing ceased. More recent testing by India and Pakistan, with

weapons in sub-megaton yields, would not have produced fallout in the northern hemisphere. The recent small kiloton North Korean tests occurred underground without generation of fallout.

The U.S. CDC (Miller and Bouville, 2005) report, 'Feasibility of a Study of the Health Effects to the American Population from Nuclear Weapons Tests Conducted by the United States and Other Nations,' includes maps of fallout levels on the United States in Chapter 3. These maps show Indiana receiving as much as 1,000 Bq/m^2 from the U.S. Pacific and Nevada weapons tests. The Beck et al. (1990) and Miller and Bouville (2005) maps show that global testing by other nations delivered greater than 6,000 Bq/m^2 to many U.S. locations. Bossew (2001) in Austria and Ritchie et al. (2009) in Arizona complement the other data.

The results of the current study appear appropriate for the levels measured in both Indiana and in the United States overall. Beck and Bennett (2002) showed a 12.7-times greater Cs-137 deposition in the United States from the later (megaton) Pacific tests than from the Nevada test series.

Cesium-137 Retention as Affected by Precipitation

In northern Indiana, the majority of Cs-137 was detected in the 91-100 cm precipitation range (Fig. 26). In the central region the majority occurred in the 101-105 cm range and to a lesser extent at 111-115 cm. In the south, Cs-137 tended to predominate in the 111-115 cm precipitation range.

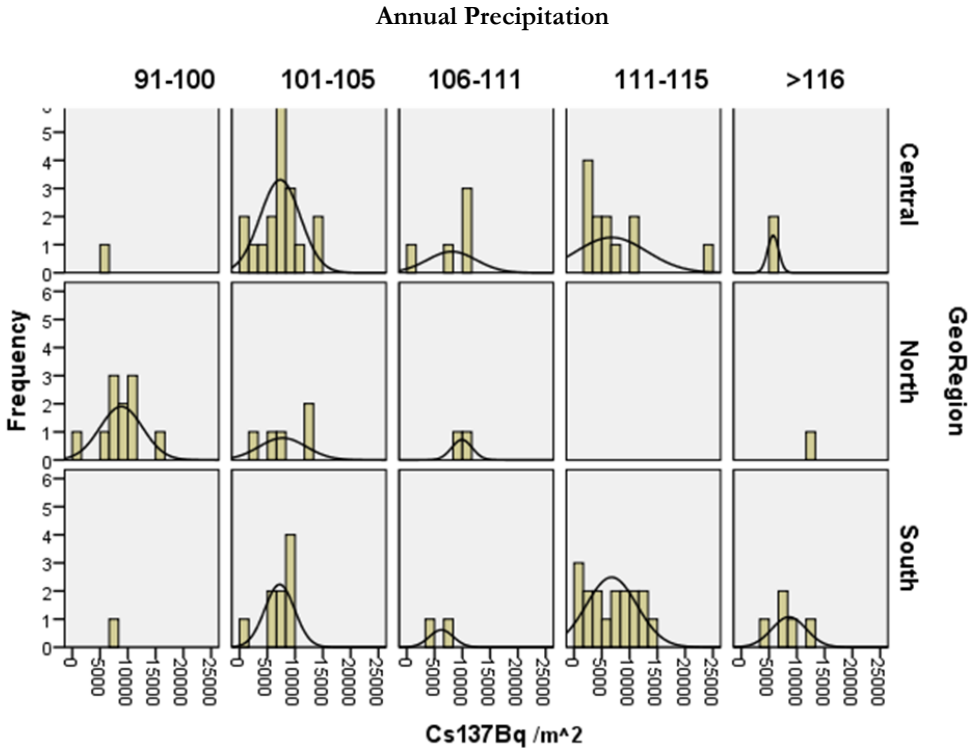

Figure 26. Retention of Cs-137 across Indiana regions as affected by precipitation

In the forest sites, Cs-137 activity tends to predominate between 6,000 and 180,000 Bq/m^2. In contrast, in the grassland sites, Cs-137 occurs primarily between 8,000 and 10,000 Bq/m^2. In addition, only 7,900 Bq of Cs-137 was detected for grassland sites receiving 91-100 cm/yr, while in forest sites values are as high as 150,000 Bq/m^2 as measured at the same rainfall level.

Weather, specifically precipitation, plays the key role in deposition of fallout (Cambray et al., 1976; Sutherland, 1996; Shand, 2013). In historic tests, especially in the U.S. Pacific, humidity and immediate rainout resulted in the locally high fallout results of the Castle Bravo Test. Since the Chernobyl and Fukushima events occurred without fireball effects, they did not

produce an immediate rainout. Because heated vapor and radioactive isotopes continued to be released from both reactors for nearly two weeks, the fallout tended to wash out from local weather events. In the current study, the regular rainfall of the eastern United States allowed for long-term deposition from the Nevada tests and the larger Pacific weapons. Following deposition in Indiana, a portion of the surface Cs-137 would have been lost via soil erosion or, more likely in forest and grassland, leached into the profile with rainfall events (Miller and Bouville, 2005).

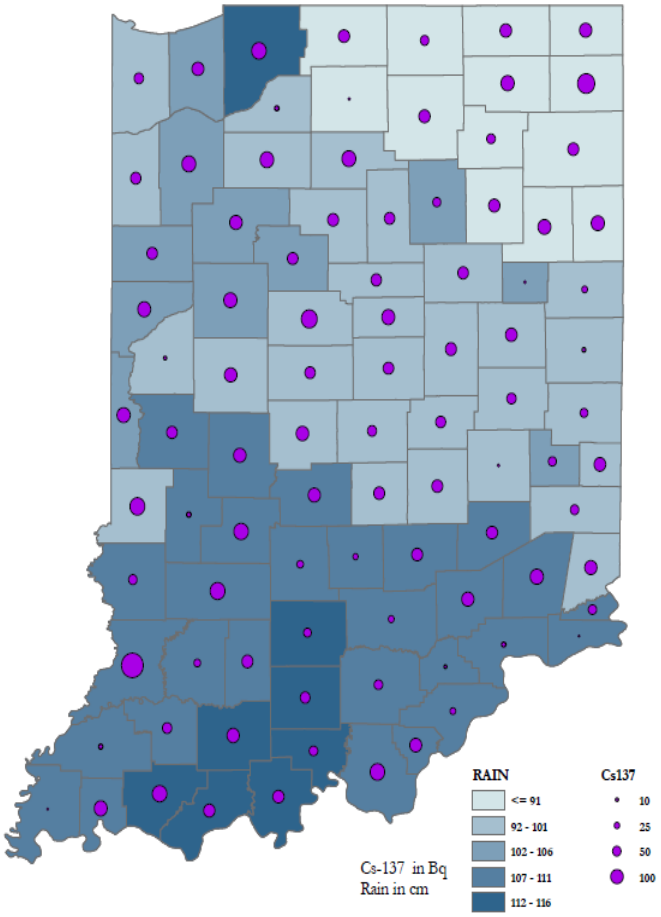

Figure 27. Map showing Cs-137 in soil compared to rainfall areas of Indiana. Data in Bq/m^2.

Arnalds et al. (1989) in Washington State, Ritchie and Henry (1990) in Georgia, and Mabit et al. (2008) in France all cite the role of water in the deposition of Cs-137 through rainfall, and its ultimate fate (i.e., whether it leaches into the soil profile or is lost in runoff to a body of water). As weather forecasting has improved, several models have emerged to explain why the eastern United States eventually received more radioactive fallout than the western half of the country.

This phenomenon has to do in part with atmospheric moisture, but it also is a function of the position of the North American continent on the globe (Reiter, 1963). Reiter (1963), drawing on the emerging knowledge of the atmosphere in that time, developed the theory of so-called 'isentropic surfaces' in which jet-stream weather systems transport clouds of fallout along a thin band. These bands are occasionally steered as a debris trajectory down from the stratosphere and into the troposphere.

Turkey, a nation with a latitude similar to Indiana, provides useful information on fallout deposition patterns. Niksarhoglu et al. (2015) collected 20 measurements across Turkey and examined the relationship of wind speed and direction to the movement of Cs-137 remaining in the atmosphere from the Chernobyl release. Deposition varied by 10-fold suggesting that Gaussian type-distribution applies to larger-size particle releases but less so to smaller-than-visible particles.

Cesium-137 Retention as Affected by Soil Clay Content

Soil samples in the current research contained a wide range of clay contents, and quantities were greatest in the south. In the medium-heavy clay category, Cs-137 ranged from 6500 to 13,800 Bq/m^2. Clay has the ability to bind readily with the Cs^+ ion. A higher level of Cs-137 generally occurs in the south (Fig. 30) than expected (given the higher rainfall). It is inferred, therefore,

that the action of clay rather than rainfall rate is the likely reason for the higher readings. Cesium is soluble in water, thus supporting movement into the soil. Figure 7 demonstrates how Cs-137 varied across Indiana by region when compared to clay content.

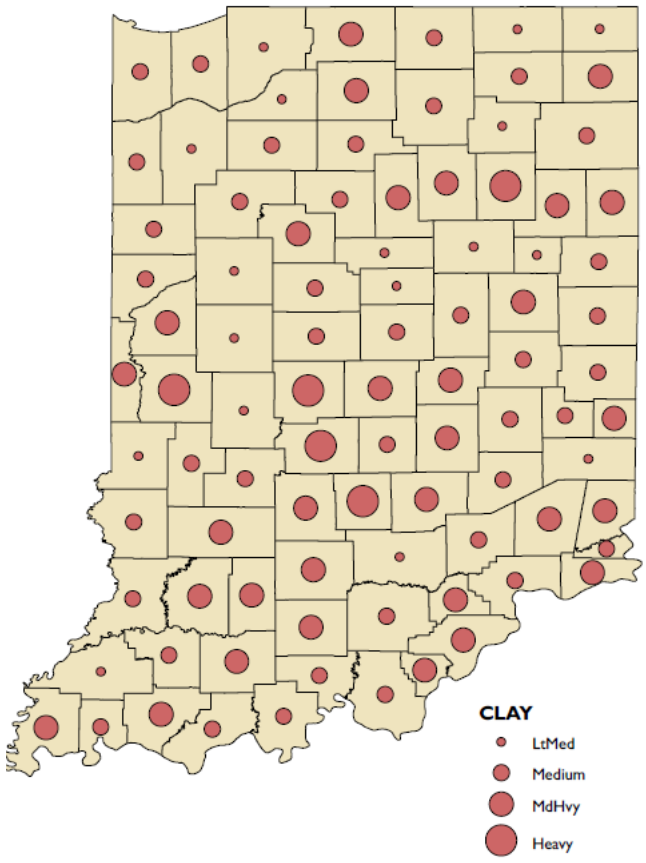

Figure 28. Estimated clay content at soil sampling sites within each county.

A variety of factors, including solution pH, ionic strength, moisture content, competitive sorption, and complexation with inorganic and organic compounds, influence the type and extent of sorption, thereby affecting the environmental transport of the Cs+ ion. The Cs+ ion does not form strong complexes with dissolved inorganic or organic compounds, so sorption of the free

ion on minerals is the dominant factor controlling its environmental fate. The major sorbents in soils are generally thought to be the layer-type silicates (Bostick et al, 2002).

The map of Indiana in Fig. 29 shows three major geographic regions, each linked to historic glacial activity. These three regions differ largely by landform –the land is nearly level in the north; land is gently rolling in the center and there are deep ravines in the south. These regions also provide an outline of precipitation, from the lowest in the north to the greatest in the south.

In the north, the Cs-137 occurred largely where the lightest rains occurred; in the central geographic region Cs-137 predominated in the three middle-level rainfall areas (101 to 111 cm) and in the southern region, the higher levels of rain contained the larger amount of Cs-137. Greater rainfall implies that more of the radioisotope will either leach or be lost in runoff rather than be retained; instead, this observation tends to decouple the relationship of rainfall to retention. The historic Cs-137 could occur either in a dry deposition or with a single rain event; if the latter it would have moved into the ground with that event. Dry deposited fallout would have moved into the ground with the next rain event or two. Therefore, the relationship between fallout in the soil and the local retention appears decoupled. Semi-arid regional studies in Arizona by Ritchie et al. (2009) found that a single rain event would move Cs-137 on to clay. Figure 32 demonstrates that the retained Cs-137 has a relationship in three different values of clay, i.e., light-medium, medium-heavy, and medium.

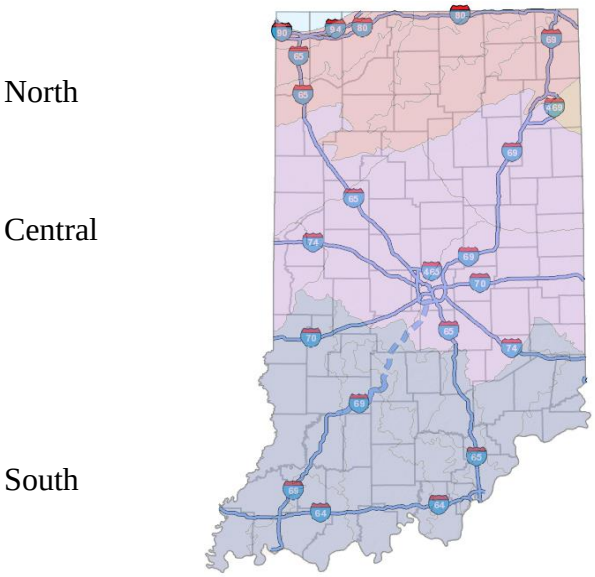

Figure 29. Geographic Regions of Indian (maps.Indiana.edu).

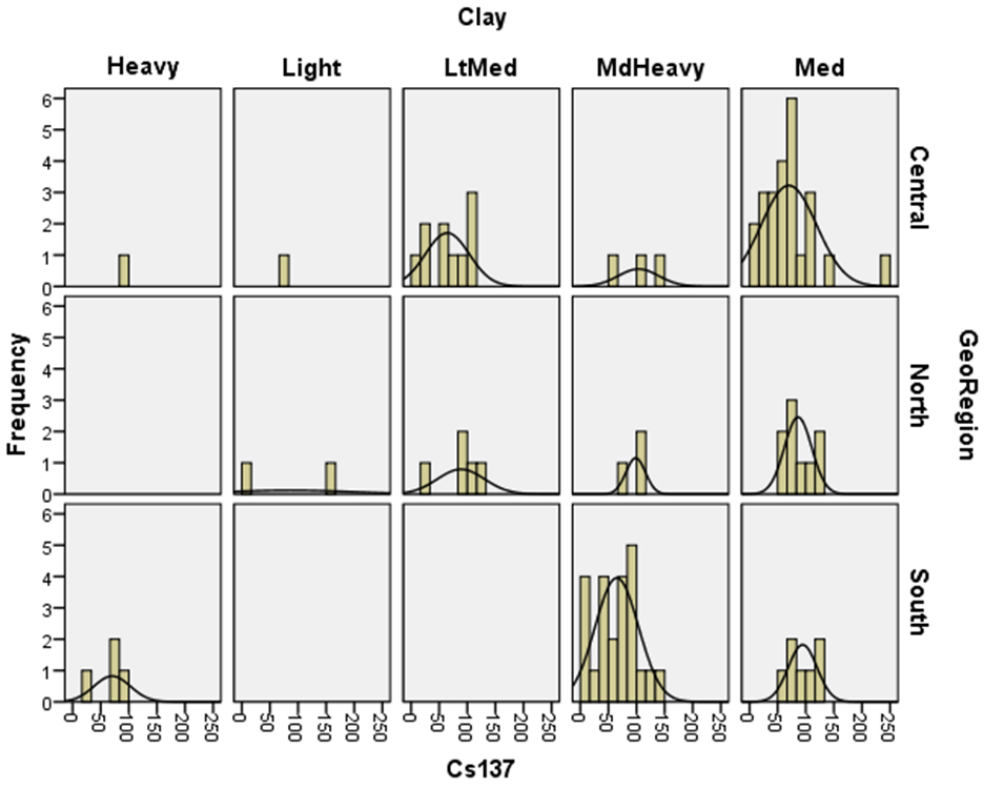

Figure 30. Cs-137 as sampled compared by clay measure and georegion.

Cesium-137 Retention as Affected by Combined Rainfall and Soil Clay Content

The soil clay contents, especially in the southern region, showed increased retention for Cs-137 (Fig. 29). The interaction of rainfall and clay demonstrated a statistically significant ($p < 0.05$) relationship. A Pearson correlation using SPSS was conducted that also included the geographic regions of Indiana. Clay content alone did not impart a significant ($p > 0.05$) difference in Cs-137 activity across the region. Clay and region were highly significantly correlated ($p < 0.01$).

Table 10: Comparison of Cs-137 content with rainfall values and clay content across the three Indiana Geographic regions

Correlations

		Cs137	Rain CM	Clay Value	GeoRegion
Cs137	Pearson Correlation	1	-.073	-.057	-.149
	Sig. (2-tailed)		.491	.591	.156
Rain cm	Pearson Correlation	-.073	1	.246*	.530**
	Sig. (2-tailed)	.491		.018	.000
Clay Value	Pearson Correlation	-.057	.246*	1	.621**
	Sig. (2-tailed)	.591	.018		.000
GeoRegion	Pearson Correlation	-.149	.530**	.621**	1
	Sig. (2-tailed)	.156	.000	.000	

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

Cesium-137 Deposition by Latitude

Palsson et al. (2013) determined, using mathematical models, that fallout predominates at 40 degrees N. latitude. The Beck and Bennett (2005) work from the 1950s through the 1960s also found that the zone between 40 and 50 degrees N. latitude had greater fallout than other regions above or below, and in both hemispheres. This would imply that jet stream patterns played a role later explained by Eitner (1963) and noted by early chase planes and radar systems (NTS, 2006). In 1966, Turner and Jennrich reported (Aberg and Hungate, 1966) that between 40^{o} and 50^{o} latitude (N. or S.) fallout deposition would be greatest. The traditional view was that weather cells, e.g., Hadley, determine how deposition would dominate at lower latitudes in the United States. Several other factors, however, including the jet stream function of the stratosphere which was largely unknown during the United States Tests in the Pacific and at Nevada, subsequently took precedent.

Potassium-40 and Lead-210 in Indiana Soil

This study measured the activity of two other radioisotopes, K-40 and Pb-210. Both isotopes, like Cs-137, have extended half-lives. Potassium-40, a near ubiquitous primordial isotope on earth not produced in any significance by a nuclear release, has a half-life of 1.25×10^{9} years. Lead-210, which exists in the soil as a decay product of uranium-238 and also from atomic weapons, has a half-life of 22.3 years. Soil K-40 ranged in activity from 16,940 (forest) to 17,463 (grassland), and Pb-210 ranged from 7,443 (grassland) to 7,449 (forest). The values for both K-40 and Pb-210 are quite similar to those for many soils in the U.S. and worldwide.

Table 11: Comparison of Cs-137, Pb-210, and K-40 activities in Indiana soils, Bq/m^2.

	Mean	Forest	Grassland
Cs-137	10,218	12,509	4,593
Pb-210	7,447	7,449	7,443
K-40	15,731	16,940	17,463

Statistical Considerations between Cs-137, Pb-210 and K-40

SPSS 24 inputs for an independent *t*-test and for a Pearson Correlation between these isotopes revealed a significant correlation between Cs-137 and K-40 but not with Pb-210. This correlation likely occurs due to the Pauling Electronegativity similarities of 0.79 for cesium and 0.82 for potassium, while lead has a value of 2.81. (Brady and Weil, 2000) state that ionic exchanges are common in soils, especially when ionic radii are similar. Since most of Indiana has a moderate pH of between 5.5 and 7.2, such exchange is likely common. Lead, however, will more rapidly attract and remain within soil, especially to clay colloids.

Table 12: Independent Samples Tests for Cs-137, Pb-210, and K-40.

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Cs-137	Equal variances assumed	.305	.582	5.507	90	.000	40.978	7.441	26.196	55.761
Pb-210	Equal variances assumed	1.136	.289	.381	90	.704	3.083	8.092	-12.994	19.159
K-40	Equal variances assumed	1.342	.250	-.601	90	.549	-7.770	12.930	-33.458	17.917

Due to the expected interaction between metal ions and clay, a further comparison of Cs-137, Pb-210 and K-40 with clay revealed a correlation between Cs-137 and K-40 (Table 13). Since both produce monovalent cations with approximately the same degree of electronegativity, this relationship seems likely but a relationship of Pb-210 with clay was not found.

Table 13: Correlations of Cs-137, Pb-210, and K-40 with clay content

		Cs-137	Pb-210	K-40	Clay
Cs-137	Pearson Correlation	1	-.071	.334**	-.057
	Sig. (2-tailed)		.499	.001	.591
Pb-210	Pearson Correlation	-.071	1	-.115	.162
	Sig. (2-tailed)	.499		.274	.122
K-40	Pearson Correlation	.334**	-.115	1	-.110
	Sig. (2-tailed)	.001	.274		.296
Clay	Pearson Correlation	-.057	.162	-.110	1
	Sig. (2-tailed)	.591	.122	.296	

**. Correlation is significant at the 0.01 level (2-tailed).

Soil pH Values

Soil samples ranged in pH from 3.1 in Orange County to over 7.0 in several locations (Table 14). Statistically relationships of Cs-137, with rain, clay or land type (forest vs. grassland) were revealed. Table 14 elabrorates on the cesium-137 by both region and the mean pH levels across sampled locations.

Table 14: Cesium-137 content and soil pH values as a function of clay classification

	Clay Classification				
	Light	Light-Medium	Medium	Medium-Heavy	Heavy
Cs-137, Bq/m^2 $x10^4$	80.30	70.52	77.80	72.36	75.65
pH, mean	6.56	6.06	6.10	6.34	6.50
n	3	15	40	29	5

Limitations of the Current Study

Types and amounts of organic matter influence retention of cations in soil. This study did not determine the quantity of soil organic matter, however. Since the goal of the current work involved determining the presence Cs-137, and comparing retention in forest to grassland ecosystems, determination of whether the Cs-137 exists at particular levels within the soil profile was not considered .

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CHAPTER 5: SUMMARY AND CONCLUSIONS

The reported research had five specific tasks. The first of these sampled for the presence of cesium-137 from radioactive fallout in soils of Indiana through a sampling effort covering all 92 counties at a depth of between 2 and 12 cm. In the second task, analysis confirmed a statistically significant greater long-term retention of Cs-137 in long-term forests over long-term grasslands. The Cs-137 exists at measureable levels, and the Indiana readings have similarity to those from other areas around the world. The data are lower for Indiana, however, than those found in studies conducted downwind of atomic bomb detonations or near reactor failure locations.

The third task examined possible correlation of Cs-137 activity with levels of clay content and rainfall levels across geographical areas of Indiana. Correlations were determined between Cs-137 and rain and geographical region. Soil pH did not correlate to Cs-137 activity and did not present a discernable pattern when mapped. The fourth task considered possible interactions of Pb-210 and K-40 with Cs-137. Cs-137 and K-40 demonstrated correlation, possibly due to chemical similarities. The four control samples, collected from locations presumed shielded from rainfall, produced evidence of air transport of sub-micron fallout.

The final task of this work included information regarding teaching activities. By involving students with nuclear science topics and methods these activities may enhance undergraduate environmental science coursework.

CHAPTER 6: RECOMMENDATIONS FOR FUTURE RESEARCH

Undergraduate environmental students could benefit from a scaled version of work carried out in the reported research. With the exception of the radiation counting system, all other methods and equipment used herein are of relatively low cost. Future undergraduate research could use a sodium iodide well counter and lightweight plastic test tubes to replicate the work. Other steps to refine this work could include accurate measure of the clay content by the hydrometer, pipette or other methods; moisture content; and ArcGIS mapping of sites with relief to measure soil erosion over time.

A number of other useful investigations are suggested.

The spectrum from the Ortec system contains information on secondary isotopes, among these, Am-241, with a half-life of 240 years. Data for this isotope might prove an interesting combination to the Cs-137 information already used here. Other isotopes, such as Tc-99 with a half-life of 211,000 years, might prove valuable for future review.

One area of research could involve how deep the Cs-137 has migrated by examining increments of 2 cm to a depth where the radioisotope has not penetrated. Soil characterization with depth might include assessment of other contaminants, organic matter, or unique combinations including Cs-137 and or other isotopes.

Since the dates of heaviest fallout in Indiana occurred between 1954 and 1965, largely from the Megaton yield weapons, dendrochronology of respective tree bands might suggest uptake levels. The Indiana experience, with perhaps 200 deposition events, might make an interesting comparison to the overwhelming influx into trees near the Chernobyl nuclear power plant release in Belarus and Ukraine. Instead of drilling as normally carried out in dendrochronology, one might extract lumber material from segments of a trunk soon after a tree

has been felled. As in the present work, Cs-137, with a unique energy, would be the isotope of choice to measure.

Testing well water could show values for Cs-137, K-40, or Pb-210 not seen in the literature. Testing recently deposited sediment in streams after a major rain event may show recent erosion of clay or other sediments containing these isotopes.

Other work might involve work across a several-acre property, perhaps 6 to 10 acres, of either long-term forest or grassland, containing enough relief to sample on hilltops, slopes and ravines or catchments or even intermittent stream bottoms for comparison of Cs-137 levels. This type of research could support soil erosion studies and allow comparison to many published works. Additionally, the data might also allow local estimation of soil loss. A related study would involve sampling in stream beds, ponds or lakes and reservoirs to determine degree of soil runoff and sediment depth. The depth of Cs-137 in sediment should be compared to data from other studies to determine differences based on latitude.

Examination of plant leaves, roots or stems may reveal uptake and accumulation of Cs-137. Based on phytoremediation research, it is highly likely that many plant species take up Cs from soil. Nearly all such studies to date relate to uptake in the wake of a major release, Additionally, different plant species will partition Cs-137 to different plant parts (e.g., roots, stems, leaves, flowers, seeds). Studies of pine nuts, acorns and other fruit may reveal the presence of low levels of this isotope. Such findings are beneficial from a public information perspective by demonstrating the presence of natural background radiation on Earth. Studies such studies can also serve to reveal higher than typical content of Cs-137 or other isotopes and there for do much to protect the public health.

CHAPTER 7: RADIATION AS A TOPIC FOR SCIENCE TEACHING

Many opportunities exist to use radioisotopes as a vehicle to enhance learning in science. With a minor investment faculty can enhance the insight students gain across many topical areas. Further, because many citizens have an innate fear of radiation, enhancing a class with occasional use of radiation-related materials will enhance the self-confidence students need to prepare as job-ready graduates.

Students need to learn the differences between ionizing and non-ionizing radiation: ionizing as either atomic material or x-rays have a connection to cancer due to the interaction of gamma rays or particles with living matter. When controlled appropriately, isotopes (atomic material) can cure diseases and stabilize malfunctioning thyroid glands. Isotopes also have great utility in industry.

Non-ionizing radiation can also cause harm yet can also offer great benefit to mankind. Non-ionizing radiation does not have a connection to cancer, but strong lasers can burn holes in steel or render people blind) while weaker ones have many uses from supermarket scanners to Lasik™ surgery. An0ther form of non-ionizing radiation, the collective radiofrequencies that allow transmission of twitter messages and telephone calls, allows meteorologists to analyze storm clouds with radar and is the active energy of microwave ovens.

Radiation demonstrates the optimism and willingness of mankind to embrace innovation, e.g., the development of the good outcomes while too often ignoring the negative side. In the early 1900s before night lighting became ubiquitous radium-226 was used to make luminous panels, lighted numbers and dials on clocks and gauges, e.g., aircraft altimeter and automobile speedometers and panels. The downside from this example became apparent when dentists noted significant jaw and bone damage from the women who painted the clock dials and other objects

and would point the brush between strokes with their tongue. Later, when scientists discovered that as little as 0.01 microgram of radium-226 could have a slow but fatal effect, this process was changed.

Students can be apprised of some of the early medical uses of radionuclides. For example, radium treatment was used for ear aches, for acne and for many other ailments, none of which persisted after 1935. For some time, a variety of patent medicines included radium-226 as an ingredient, and the use of water jars made from granite containing this isotope would allow some of it to dissolve into the water and finally to the consumer.

How we control radiation preceded most of the modern environmental regulations and therefore can provide a basis on how the United States Code is developed, and from there how the working regulations, i.e., the Code of Federal Regulations, developed and has specialization among the many titles. This brings up an interesting dichotomy: in our time the Nuclear Regulatory Commission (NRC) oversees the use of radioactive materials (isotopes) in civilian use and the Food and Drug Administration oversees electrically generated radiation products, which includes all x-ray categories, lasers and all radiofrequency systems. However, the great difference here is that the NRC (directly or through some Agreement States) licenses, authorizes possession and use, inspects and can even fine those who fail to live up to their license agreement. The FDA, however, sets limits for emissions and controls for original models, often based on energy level; however, these standards apply to the manufacturer and not to the purchaser or user. Many states inspect x-ray machines but standards and quality will vary.

Students can hear a presentation or work through an online module on Title 10 CFR to learn the structure of the Code of Federal Regulations as this Title, from parts 1 to 199, has far less complexity than most others. From there, students can easily work with Title 40

(Environmental); Title 49 (Transportation); Title 29 (Labor) which includes Occupational Safety and Health, or others. How these regulations begin, how the comment periods work, who and when citizens, groups, trade associations and even labor unions can comment before a regulation changes or a new one goes into effect has significant impact on any student in the environmental field. Most or all environmental topics have potential for significant litigation, and records about training, testing, field operations, and calibrations all have significance to make students very successful.

By taking part in a notional nuclear release, students can gain experience in the structure of a major response at the state or federal level and could benefit from preparing information for public officials on guidance for the public. In so doing the students gain the experience of preparing succinct and direct written and oral communications.

One of the greater challenges facing the world of tomorrow involves energy resources. Students must be equipped to understand the environmental, economic, social and political underpinnings of the different energy options, which will become more important over the coming decades. Understanding cradle to grave analysis, reliability of choices, recycling of nuclear materials and the legacy of environmental wastes from earlier periods covered in class will help those students with future vocational and voting choices. The complexity of the problem, and the geography and the resources of the United States require complex thinking and will therefore contain many new working situations that do not exist today.

The subject of confidence may provide a pathway greater understanding (Boydell, 2016). As a starting point one can ask students, in any kind of exercise or discussion, to develop a list of media characters who owe their super-strength to some kind of radiation, e.g., the Hulk or Superman. Having students describe how these characters and situations have logical errors

provides a method to develop peer or group participation. When reading articles about the early use of radium e.g., the case of the watch dial painters (Clark, 1991), or viewing a video on the legal action of this story, students often wonder how such events could possibly occur. One should then invite a review of how radiation has improved health care with treatments for cancer, thyroid imbalance and more. Students then go through what Mezirow referred to as a disorienting dilemma, which Boydell (2016) has expanded.

The disorienting dilemma situation exists when students see the unexpected in a subject they believe they understand, but find out that reality presents them with the unexpected. Encouraging students to work through the unexpected can lead to new insights (Brookfield, 1987) and confidence (Boydell, 2016). Examples of how faculty can introduce radioactive materials to enhance their subjects follow. In the contrast between good uses and poor uses of radiation, students will question why the benefits seemed more attractive than the limitations. In the case of the radium overuse/misuse, one realizes that implementation came about before full effects were understood.

A discussion with students of the Periodic Table of the Elements allows one to ask why so many of the atomic masses have odd decimal values. With selection of some simpler isotopes, e.g., hydrogen (having alternative isotopic forms deuterium and tritium) one can find the relative contribution of the three together. As the math extends out to several decimals, students learn how subtle differences can change the physical attributes of an atom (Claesen et al., 2012).

Students can learn that analysis of rainwater helps determine if that water originated from the Pacific Ocean or the Gulf of Mexico. Oxygen has three stable isotopes among its 13 different isotopes. Stable O-18, with 2 more neutrons than ‘normal’ O-16, precipitates out earlier in rain clouds due to its slightly greater mass. If rainwater has no O-18, the precipitation likely

originated from evaporation over the Midwest because rainwater from the Pacific, having more O-18, will likely drop more in the far West. Rainfall from storms formed over Illinois will likely have a very low content of O-18.

For many, the most interesting aspects of radiation occur when students examine the world of the very small. Radiation, beginning with the Curies in the late 1890s, developed the 'Curie' as a unit of measure of the activity contained in a gram of one type of radium (Ra-226). The Curie, amounting to 3.7×10^{10} disintegrations per second, allows the introduction of exponential numbers and prefixes such as milli- and micro-. As a follow-on students can learn about the Becquerel unit, now part of the metric system (*Systeme Internationale*). Becquerels refer to a single disintegration event and so the practical use of Becquerels involves the use of multipliers like Mega- and Giga- as prefixes.

A major aspect of the current environmental debate involves how to produce electricity decades from now. Most students understand the significant hidden price of coal and its impact on health and the environment and yet have fear about the dangers of nuclear energy. With careful consideration, the world energy balance becomes clearer and the choices for the United States have greater variety due to the abundance of our natural resources. However, this kind of debate can include world population shifts, energy demand, international political tensions, infrastructure types, carbon budgets and potential for release of mercury. Newer textbooks (e.g., Christensen and Legge, 2016) feature the struggles and challenges of the energy and other debates; however, rather than viewing these topics as separate entities, students learn more, retain more and gain greater insight when covering these topics concurrently. Because the global situation (environmental, political, economic, etc.) often changes more quickly than textbooks have revisions, the use of current events, certainly as the ability to electronically research topics

grows, can rapidly enhance learning (Romano, 2011). In turn, this can further facilitate personal and group interaction (Song and Schwenz, 2013).

A skill set of great importance involves capturing data, graphing the results and then explaining what the graph shows. Many matters in the environmental arena can end up in litigation and students who understand the importance of recording and interpreting data will have greater success in their career from those who do not acquire this skill.

An emerging method to enhance student learning involves the exploration of student talent (Brookfield, 1987) in which an instructor challenges students to develop a video, song, poster, puzzle or even an electronic or board game to enhance learning. As Brookfield points out, exploiting all the talent in a class produces many rewards.

Specific radiation exercises with small commercially available point sources can provide a variety of learning and confidence building activities, e.g., students can learn meter operational checks and how to diagnose if a meter performs within set parameters. They can learn to survey, and then compare their results to those of other students.

With minor effort, small boxes, or jigs, the size of the meter probe, can allow the meter to remain fixed at a set height over a known source. From there, different shielding materials allow the students to determine if the source in the jig is a gamma isotope, a beta isotope or an alpha isotope by observing changes when paper, foil, thin sheets of foil, or sheets of steel or copper in turn get placed between the source and the probe. Alphas shield readily, betas less so and gamma would pose the greater shielding concern.

Using a soil sampling hammer similar to the one used in the current study, students can learn to extract, label, and then conduct field tests before drying, crushing, sieving to conduct other analyses, such as mineral content, soil chemistry, or related tests.

Ultimately, the object of developing the best-trained graduates in environmental areas is the object of a process termed ‘transformational learning,’ which is advanced by many. In particular, as Uyanki (2016) states, our end objective should involve the permanency of learning. Periodic hands-on methodology, e.g., taking radiation measurements in the environment and with known small check sources, adds both a practical aspect to learning and helps develop students’ capabilities in new and permanent ways.

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GLOSSARY AND ACRONYMS

AEC - Atomic Energy Commission. Federal agency which succeeded the Manhattan Project. Later was split into the U.S. Department of Energy and the U.S. Nuclear Regulatory Commission.

Becquerel - A single radioactive decay event.

Biological half-life - Time for one-half of an ingested substance to clear the body.

Castle Bravo – Nuclear test conducted in 1954. 'Castle' describes the test series at the Marshall Islands; 'Bravo' was the test name.

Cesium-137 - a radioactive form of cesium with a unique energy and a 30-year half-life.

Cold War – The period of tension between the United States and former Soviet Union, from 1947 until the end of the Soviet Union in 1991, during which nations both built and tested nuclear weapons.

Critical mass – The state at which a nuclear weapon or a nuclear power plant reactor releases energy. When controlled, electricity may be generated. When uncontrolled, as in a nuclear weapon, prompt detonation occurs.

Curie - Traditional measure of decay, amounting to 3.7 x1010 Becquerels.

DOD – U.S. Department of Defense. Created in 1947 to merge the Army, Navy (with the Marine Corps) and the just-formed Air Force.

DOE – U.S. Department of Energy. Developed when the Atomic Energy Commission split; DOE builds, owns and maintains nuclear weapons.

Dose – Measure of radiation exposure potential typically read by handheld radiation meters in either RAD/hour (or subunits); now converted to Grays.

Dose equivalent – Biological dose from ionizing radiation exposure, formerly measured in REM and now in Sieverts.

Dosimeter – Formerly film badges; now lithium flouride chips or electronic devices capable of recording the total accumulation of radiation energy received by the body. Formerly reported in milliREM but now reported in milliSieverts

Gray – Measure of the radiation detected by a meter; equated to the formerly-used Radiation Absorbed dose (RAD). Used for safety purposes.

Half-life – Period of time in which one-half of a quantity of radioactive material transforms by decay to another radioisotope or stable isotope. Each isotope has a specific half-life.

Hardening [of a structure] – Process of shielding electronics for survivability from the early effects of a nuclear weapon, e.g., prompt energy release.

HASL - DOE Health and Safety Laboratory - Original test facility in the United States for fallout studies.

EML - DOE-Energy Measurements Laboratory. Name change of the HASL; continues today.

Detonation – Explosive release of a nuclear weapon.

Element - Name of a chemical element, based on its structure and properties; most have isotopes.

Effective half-life - The combined effect of the biological and physical half-lives of an isotope; used to calculate clearing times of radioisotopes inhaled, ingested or administered.

Fallout - Debris from a nuclear release; the smallest particles may remain aloft for several years.

Fission - Atom splitting, typically of U-235 into characteristic isotopes and release of energy.

Fusion - The joining by force of lighter elements which results in the release of large quantities of energy.

Ground Zero - Detonation point of a nuclear weapon.

I-131 - Iodine-131. A gaseous isotope released by a weapon or reactor. This isotope is readily taken up by mammals and poses a significant medical concern.

Isotope – A form of an element having more or less neutrons in its nucleus as compared with the most common form. Many isotopes decay through radioactive transformations, i.e., alpha, beta, gamma or neutron, to become stable.

Isotope Ratios - Comparison of one ratio to another to learn the origins of a radiation release via a weapon or nuclear power reactor failure.

Lichen - a plant with both photosynthetic and non-photosynthetic adaptions.

Lucky Dragon (translated from Daigo Fukuryu Maru) – Japanese vessel covered by fallout from the Castle Bravo nuclear test.

Manhattan Project - The military and civilian program to build an atomic bomb during World War 2.

Marshall Islands - That part of the Pacific Test Range (now inactive) for testing of nuclear weapons after World War 2; site of 62 tests including 18 megaton weapons. Site of Castle Bravo incident.

Metric radiation units - Used as Grays/hour for surveys and integrated to Sieverts with integration of time; today, Sievert records come from dosimetry devices worn by those employed specifically as radiation workers.

Neutron activation – Process within an operating reactor or very briefly after a nuclear weapon detonation, when neutrons help continue the fission process. Some released neutrons cause some non-radioactive isotopes to become radioactive, which then follow a predictable half-life.

Nevada Test Site – Facility which opened in 1947 to test above- and below-ground nuclear

weapons; more than 100 above-ground and 921 below-ground tests occurred here. The last large test, 'Sedan,' occurred in July 1962.

Physical half-life - Decay time for one-half a radioactive isotope to decay; each radioisotope has a characteristic half-life.

RAD – Standard unit for field measurements of radiation which predominated after 1948, replacing the Roentgen and REP (Radiation Equivalent Person). The Gray now has replaced the RAD, although the older unit remains in common use in the US.

Radiation Survey – Survey of ambient radiation typically performed with hand-held meters; now also possible from aircraft and drones.

Radionuclide - Synonym for radioisotope.

Reactor/Nuclear Power Plant – Facility typically used to generate electricity. Some reactors transform U-235 to plutonium-239 for nuclear weapons.

Release – Dispersal of radioactive debris following detonation of a nuclear weapon or failure of a nuclear reactor.

REM – Radiation Equivalent Man – The standard reporting unit of actual exposure to people based on the type of radiation, to include the differing damage potential, from alpha, beta, gamma, neutrons or x-rays. The metric unit Sievert has recently replaced the REM.

Rongerick - Atoll in South Pacific where a group of weather observers sheltered in place when Castle Bravo fallout arrived in 1954.

Rongerlap - Atoll in South Pacific where several hundred inhabitants were injured by fallout from the Castle Bravo test. Inhabitants later moved away due to contamination by fallout.

Sievert – Unit of radiation exposure to people using the System Internationale (SI). The currently internationally recognized metric analog to the REM.

Soviet Union - The Union of Soviet Socialist Republics, an ally of the United States and the non-Axis powers against Germany and Japan in World War 2. It became a U.S. adversary and developed a significant nuclear weapons arsenal beginning after World War 2. Detonated its first nuclear weapons in August 1949.

Sr-90 - Strontium-90. A major radioactive isotope occurring in fallout, with a long-term half-life of 28 years.

Stratosphere - Division of the atmosphere above the troposphere.

Traditional units - Roentgen, RAD, and REM were used for radiation surveys and all medical uses until the adoption of the metric system (Systeme Internationale) in the 1980s.

Trinity Site - Site near Alamogordo, New Mexico, where the first nuclear weapon from the Manhattan project was detonated.

Troposphere - Lowest level of the atmosphere containing most weather effects.

Uranium-233 and Uranium-235 – Radioactive isotopes of uranium. Both can be refined from large quantities of ore containing mostly U-238. Both U-235 and U-233 can fission under the proper conditions; however, U-233 is so rare that it rarely contributes to a weapon.

Whole Body Exposure - Surveys intended to keep people safe from radiation effects; originally recorded in R/hr, and later Rads/hr. Later switched to Grays.

Yield – The energy release of a nuclear weapon when compared to tons of conventional (TNT) explosives.

APPENDICES

Table A.1 Forest Values for Cs-137, Pb-210, and K-40 and various parameters

County	Cs137 Bq/m^2	Pb210 Bq/m^2	K40 Bq/m^2	Land Type	Precip cm	Clay Value	Geo Region	pH
Adams	10900	479600	18966	Forest	101	MdHeavy	North	6.1
Allen	7957	904700	22999	Forest	91	Med	North	6.2
Bartholomew	8393	697600	19184	Forest	111	Med	South	6.2
Boone	7085	577700	23762	Forest	101	Med	Central	5.0
Brown	2398	741200	10791	Forest	111	Heavy	South	6.8
Carroll	7739	664900	11881	Forest	106	MdHeavy	South	6.0
Cass	8066	1024600	22563	Forest	101	Med	Central	5.5
Clinton	14388	577700	23326	Forest	101	Med	Central	6.5
Dearborn	9701	555900	18530	Forest	101	MdHeavy	South	6.6
Decatur	7848	872000	14170	Forest	111	Med	Central	6.5
DeKalb	16350	675800	22018	Forest	91	Light	North	5.3
Delaware	9374	850200	20165	Forest	99	MdHeavy	South	7.2
Dubois	9701	664900	11881	Forest	116	MdHeavy	South	5.7
Elkhart	5450	337900	15260	Forest	91	Med	North	7.4
Floyd	8611	741200	15478	Forest	101	MdHeavy	South	5.2
Fulton	11990	621300	16023	Forest	101	Med	North	6.6
Grant	6976	981000	10900	Forest	101	Light	Central	6.9
Greene	13843	817500	18857	Forest	111	MdHeavy	South	6.6
Hancock	6431	937400	16241	Forest	101	MdHeavy	South	6.4
Harrison	12862	719400	16786	Forest	111	Med	South	4.3
Hendricks	9701	828400	17658	Forest	101	Heavy	Central	6.2
Henry	5668	664900	16677	Forest	101	Med	Central	6.6
Huntington	8175	1144500	10464	Forest	91	Heavy	South	5.3
Jackson	2616	817500	5450	Forest	111	LtMed	Central	6.6
Jefferson	1853	719400	13407	Forest	111	Med	Central	6.3
Jennings	10137	577700	21364	Forest	111	Med	Central	6.5
Johnson	8393	523200	17658	Forest	101	Med	Central	7.6
Knox	24634	468700	18094	Forest	111	Med	Central	6.5
Kosciusko	7957	664900	16350	Forest	91	Med	North	5.8
LaGrange	8720	588600	22454	Forest	91	LtMed	North	6.5
Lake	5886	566800	18203	Forest	101	Med	North	4.8

County	Cs-137 Bq/m^2	Pb-210 Bq/m^2	K-40 Bq/m^2	Land Type	Precip. Cm	Clay Level	Geo Region	pH
LaPorte	12971	523200	22563	Forest	116	LtMed	North	4.9
Madison	7957	1700400	20274	Forest	101	Med	Central	6.1
Marion	5886	2289000	15587	Forest	101	MdHeavy	South	6.4
Marshall	763	1122700	218	Forest	91	Light	North	7.5
Martin	7848	915600	12426	Forest	111	MdHeavy	South	6.5
Miami	6976	1035500	11227	Forest	101	MdHeavy	South	6.7
Monroe	3597	1013700	14061	Forest	111	MdHeavy	South	6.8
Montgomery	9483	763000	19184	Forest	101	LtMed	Central	7.1
Morgan	9919	861100	12644	Forest	111	Heavy	South	7.1
Newton	7085	348800	11118	Forest	101	Med	North	5.4
Noble	10791	436000	21146	Forest	91	Med	North	7.1
Owen	12317	752100	17331	Forest	111	Med	South	5.1
Parke	7630	414200	21037	Forest	111	Heavy	South	7.1
Perry	7848	915600	19620	Forest	116	Med	South	5.7
Pike	5886	490500	20710	Forest	111	Med	South	5.5
Porter	8611	1079100	18094	Forest	106	Med	North	6.6
Pulaski	11881	446900	14170	Forest	101	Med	North	4.6
Putnam	10028	1090000	22890	Forest	111	LtMed	Central	6.0
Ripley	11118	501400	19511	Forest	111	MdHeavy	South	7.0
Shelby	8284	490500	19620	Forest	101	MdHeavy	South	7.3
Spencer	8175	872000	13516	Forest	116	Med	South	6.4
St Joseph	7848	392400	17113	Forest	91	MdHeavy	North	6.5
Steuben	9483	675800	18203	Forest	91	LtMed	North	5.8
Switzerland	654	577700	218	Forest	111	MdHeavy	South	6.4
Tippecanoe	11118	566800	23762	Forest	106	LtMed	Central	6
Tipton	11009	1035500	26378	Forest	101	LtMed	Central	5.3
Vanderburg	10573	675800	19075	Forest	111	Med	South	5.4
Vermillion	11118	664900	23980	Forest	106	MdHeavy	Central	6.6
Vigo	13516	861100	20165	Forest	111	MdHeavy	Central	6.4
Wabash	4687	512300	1417	Forest	98	MdHeavy	South	6.5
Warren	10355	697600	23435	Forest	106	Med	Central	7.5
Warrick	12862	577700	20383	Forest	116	MdHeavy	South	7.1
Wells	10791	1373400	11118	Forest	104	MdHeavy	North	5.6
Whitley	5123	370600	15587	Forest	91	LtMed	Central	6.7

Table A.2 Grassland Values for Cs-137, Pb-210, and K-40 and various parameters

County	Cs-137	Pb-210	K-40	Land	Precip	Clay	Geo	
	Bq/m^2	Bq/m^2	Bq/m^2	Type	cm	Value	Region	pH
Benton	7085	501400	16568	Grassland	106	Med	Central	7.5
Blackford	763	250700	2507	Grassland	107	LtMed	Central	3.9
Clark	2616	643100	17985	Grassland	111	MdHeavy	South	4.6
Clay	1853	621300	28994	Grassland	111	Med	Central	6.6
Crawford	5014	664900	11990	Grassland	116	Med	Central	4.4
Daviees	3379	872000	24416	Grassland	111	MdHeavy	South	7.1
Fayette	4796	479600	24416	Grassland	111	Med	Central	7.1
Fountain	981	490500	19402	Grassland	101	MdHeavy	South	7.3
Franklin	5450	773900	21146	Grassland	101	LtMed	Central	6.8
Gibson	1744	305200	18530	Grassland	111	LtMed	Central	7.1
Hamilton	7085	784800	28449	Grassland	101	Med	Central	6.2
Howard	7085	425100	17549	Grassland	101	LtMed	Central	6.8
Jasper	11227	392400	15260	Grassland	106	LtMed	North	5.3
Jay	2834	610400	25506	Grassland	100	Med	Central	7.2
Lawrence	4360	490500	19075	Grassland	116	MdHeavy	South	6.4
Ohio	4905	621300	14824	Grassland	111	Med	Central	7.1
Orange	6431	2921200	19947	Grassland	116	MdHeavy	Central	3.8
Posey	654	730300	23544	Grassland	111	MdHeavy	South	6.3
Randolph	1635	599500	15478	Grassland	101	Med	Central	4
Rush	763	1122700	218	Grassland	101	Med	Central	6
Scott	1199	1547800	218	Grassland	111	MdHeavy	South	5.7
Starke	1962	545000	22563	Grassland	101	LtMed	North	6.1
Sullivan	5232	610400	25179	Grassland	111	Med	Central	6.8
Union	8720	523200	15696	Grassland	101	MdHeavy	South	7
Washington	5232	436000	16132	Grassland	111	Med	Central	6.8
Wayne	4796	991900	14497	Grassland	101	Med	Central	4

Table A3. Precipitation Analysis Overall – Cs137

Oneway

Descriptives

Cs137 from initial data

Precipitation	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1Light	13	77.85	33.561	9.308	57.57	98.13	7	150
2 Light Med	34	67.76	32.197	5.522	56.53	79.00	7	132
3 Medium	11	73.91	30.231	9.115	53.60	94.22	7	103
4 Med Hvy	26	61.54	49.243	9.657	41.65	81.43	6	226
5 Heavy	8	77.25	29.932	10.583	52.23	102.27	40	119
Total	92	68.99	37.370	3.896	61.25	76.73	6	226

ANOVA

Cs137

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	3326.309	4	831.577	.585	.675
Within Groups	123758.681	87	1422.514		
Total	127084.989	91			

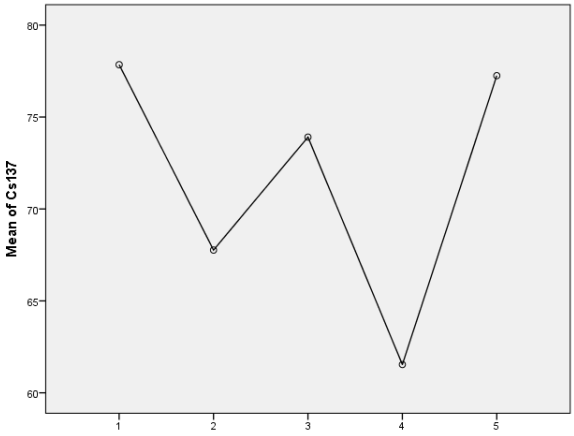
Table A4. Multiple Comparisons- Cs-137 and Precipitation (Bonferroni)

Multiple Comparisons

Dependent Variable: Cs137 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 Light	2 Lt Medium	10.081	12.299	1.000	-25.34	45.51
	3 Medium	3.937	15.451	1.000	-40.57	48.44
	4 Med Heavy	16.308	12.812	1.000	-20.59	53.21
	5 Heavy	.596	16.948	1.000	-48.22	49.41
2 Light Medium	1 Light	-10.081	12.299	1.000	-45.51	25.34
	3 Medium	-6.144	13.083	1.000	-43.83	31.54
	4 Med Heavy	6.226	9.826	1.000	-22.08	34.53
	5 Heavy	-9.485	14.821	1.000	-52.17	33.20
3 Medium	1 Light	-3.937	15.451	1.000	-48.44	40.57
	2 Lt Medium	6.144	13.083	1.000	-31.54	43.83
	4 Med Heavy	12.371	13.566	1.000	-26.70	51.45
	5 Heavy	-3.341	17.525	1.000	-53.82	47.14
4 Med Heavy	1 Light	-16.308	12.812	1.000	-53.21	20.59
	2 Lt Medium	-6.226	9.826	1.000	-34.53	22.08
	3 Medium	-12.371	13.566	1.000	-51.45	26.70
	5 Heavy	-15.712	15.249	1.000	-59.63	28.21
5 Heavy	1 Light	-.596	16.948	1.000	-49.41	48.22
	2 Lt Medium	9.485	14.821	1.000	-33.20	52.17
	3 Medium	3.341	17.525	1.000	-47.14	53.82
	4 Med Heavy	15.712	15.249	1.000	-28.21	59.63



1 Light…… 5 Heavy

Table A5. Rainfall analysis Grassland only – Cs137 Oneway Descriptives

Oneway

Descriptives

Cs137 from initial data

Precipitation	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1 Light	13	77.85	33.561	9.308	57.57	98.13	7	150
2 Lt Medium	24	80.21	25.790	5.264	69.32	91.10	24	132
3 Medium	7	78.00	23.424	8.853	56.34	99.66	43	102
4 Med Heavy	16	81.88	52.294	13.073	54.01	109.74	6	226
5 Heavy	5	94.60	22.744	10.172	66.36	122.84	72	119
Total	65	81.02	34.537	4.284	72.46	89.57	6	226

ANOVA

Cs137 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	1144.384	4	286.096	.228	.921
Within Groups	75194.601	60	1253.243		
Total	76338.985	64			

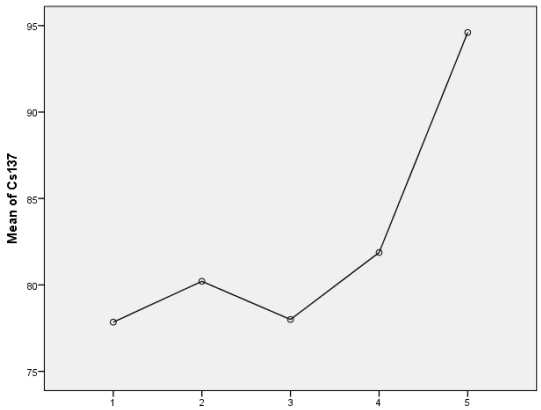
Table A6. Multiple Comparisons – Cs-137 and Bonferroni

Multiple Comparisons

Dependent Variable: Cs137 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 Light	2 Lt Medium	-2.362	12.191	1.000	-37.89	33.17
	3 Medium	-.154	16.596	1.000	-48.52	48.22
	4 Med Heavy	-4.029	13.219	1.000	-42.56	34.50
	5 Heavy	-16.754	18.629	1.000	-71.05	37.54
2 Light Med	1 Light	2.362	12.191	1.000	-33.17	37.89
	3 Medium	2.208	15.207	1.000	-42.11	46.53
	4 Med Heavy	-1.667	11.426	1.000	-34.97	31.63
	5 Heavy	-14.392	17.403	1.000	-65.11	36.33
3 Medium	1 Light	.154	16.596	1.000	-48.22	48.52
	2 Lt Medium	-2.208	15.207	1.000	-46.53	42.11
	4 Med Heavy	-3.875	16.043	1.000	-50.63	42.88
	5 Heavy	-16.600	20.729	1.000	-77.02	43.82
4 Medium Heavy	1 Light	4.029	13.219	1.000	-34.50	42.56
	2 Lt Medium	1.667	11.426	1.000	-31.63	34.97
	3 Medium	3.875	16.043	1.000	-42.88	50.63
	5 Heavy	-12.725	18.138	1.000	-65.59	40.14
5 Heavy	1 Light	16.754	18.629	1.000	-37.54	71.05
	2 Lt Medium	14.392	17.403	1.000	-36.33	65.11
	3 Medium	16.600	20.729	1.000	-43.82	77.02
	4 Med Heavy	12.725	18.138	1.000	-40.14	65.59



1 Light……. Precipitation…… 5 Heavy

Table A7. Preciptiation Grassland only – Cs137 Oneway Descriptives

Oneway

Descriptives

Cs137 from initial data

	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
2 Lt Medium	10	37.90	26.409	8.351	19.01	56.79	7	80
3 Medium	4	66.75	42.914	21.457	-1.54	135.04	7	103
4 Med Heavy	10	29.00	16.323	5.162	17.32	40.68	6	48
5 Heavy	3	48.33	9.713	5.608	24.21	72.46	40	59
Total	27	40.04	26.828	5.163	29.42	50.65	6	103

ANOVA

Cs137 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	4324.646	3	1441.549	2.304	.104
Within Groups	14388.317	23	625.579		
Total	18712.963	26			

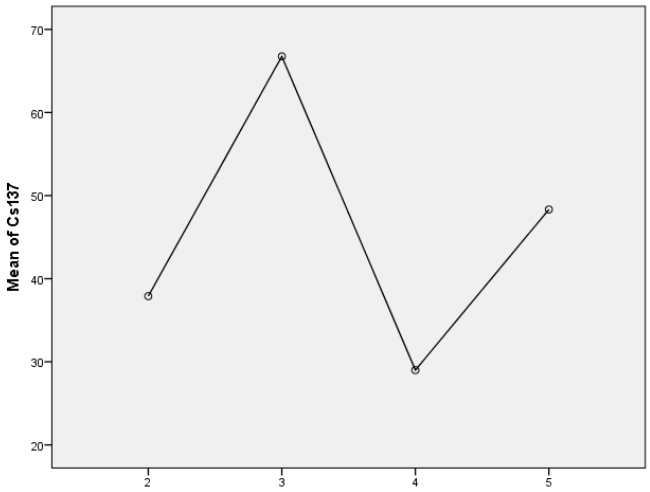
Table A8. Multiple Comparisons – Grassland

Multiple Comparisons

Dependent Variable: Cs137 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2 Light Medium	3 Medium	-28.850	14.797	.381	-71.56	13.86
	4 Med Heavy	8.900	11.186	1.000	-23.38	41.18
	5 Heavy	-10.433	16.465	1.000	-57.95	37.09
3 Medium	2 Lt Medium	28.850	14.797	.381	-13.86	71.56
	4 Med Heavy	37.750	14.797	.107	-4.96	80.46
	5 Heavy	18.417	19.103	1.000	-36.72	73.55
4 Med Heavy	2 Lt Medium	-8.900	11.186	1.000	-41.18	23.38
	3 Medium	-37.750	14.797	.107	-80.46	4.96
	5 Heavy	-19.333	16.465	1.000	-66.85	28.19
5 Heavy	2 Lt Medium	10.433	16.465	1.000	-37.09	57.95
	3 Medium	-18.417	19.103	1.000	-73.55	36.72
	4 Med Heavy	19.333	16.465	1.000	-28.19	66.85



1 Light……... Precipitation……..…… 5 Heavy

Table A9. Precipitation analysis overall Pb210

Oneway

Descriptives

Pb210 from initial data

Precipitation	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1 Light	13	64.69	30.641	8.498	46.18	83.21	31	126
2 Light Med	34	72.38	34.309	5.884	60.41	84.35	32	210
3 Medium	11	52.82	19.338	5.831	39.83	65.81	23	99
4 Med Heavy	26	65.50	23.341	4.578	56.07	74.93	28	142
5 Heavy	8	87.50	74.268	26.258	25.41	149.59	45	268
Total	92	68.33	35.177	3.667	61.04	75.61	23	268

ANOVA

Pb210 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	6525.282	4	1631.321	1.338	.262
Within Groups	106080.935	87	1219.321		
Total	112606.217	91			

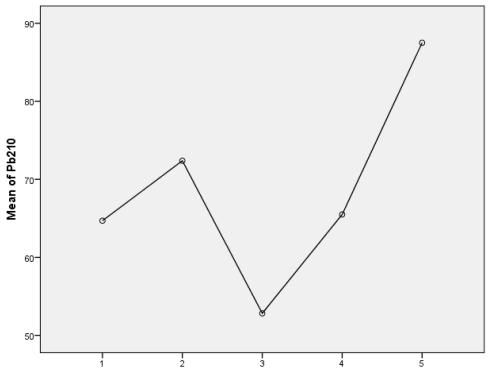
Table A10. Multiple Comparison Pb-210

Multiple Comparisons

Dependent Variable: Pb210 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 Light	2 Lt Medium	-7.690	11.387	1.000	-40.49	25.11
	3 Medium	11.874	14.305	1.000	-29.33	53.08
	4 Med Heavy	-.808	11.861	1.000	-34.97	33.36
	5 Heavy	-22.808	15.691	1.000	-68.00	22.39
2 Light Medium	1 Light	7.690	11.387	1.000	-25.11	40.49
	3 Medium	19.564	12.112	1.000	-15.32	54.45
	4 Med Heavy	6.882	9.097	1.000	-19.32	33.09
	5 Heavy	-15.118	13.721	1.000	-54.64	24.41
3 Medium	1 Light	-11.874	14.305	1.000	-53.08	29.33
	2 Lt Medium	-19.564	12.112	1.000	-54.45	15.32
	4 Med Heavy	-12.682	12.560	1.000	-48.86	23.49
	5 Heavy	-34.682	16.225	.354	-81.42	12.05
4 Med Heavy	1 Light	.808	11.861	1.000	-33.36	34.97
	2 Lt Medium	-6.882	9.097	1.000	-33.09	19.32
	3 Medium	12.682	12.560	1.000	-23.49	48.86
	5 Heavy	-22.000	14.118	1.000	-62.66	18.66
5 Heavy	1 Light	22.808	15.691	1.000	-22.39	68.00
	2 Lt Medium	15.118	13.721	1.000	-24.41	54.64
	3 Medium	34.682	16.225	.354	-12.05	81.42
	4 Med Heavy	22.000	14.118	1.000	-18.66	62.66



1 Light…….. Precipitation… 5 Heavy

Table A11. Precipitation analysis Forest only Pb210

Oneway

Descriptives

Pb210 from initial data

Precipitation	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1 Light	13	64.69	30.641	8.498	46.18	83.21	31	126
2 Light Med	24	76.29	38.256	7.809	60.14	92.45	32	210
3 Medium	7	61.29	18.191	6.875	44.46	78.11	45	99
4 Md Heavy	16	67.06	17.741	4.435	57.61	76.52	38	100
5 Heavy	5	65.20	16.084	7.193	45.23	85.17	48	84
Total	65	69.23	29.243	3.627	61.98	76.48	31	210

ANOVA

Pb210 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2062.645	4	515.661	.587	.673
Within Groups	52668.894	60	877.815		
Total	54731.538	64			

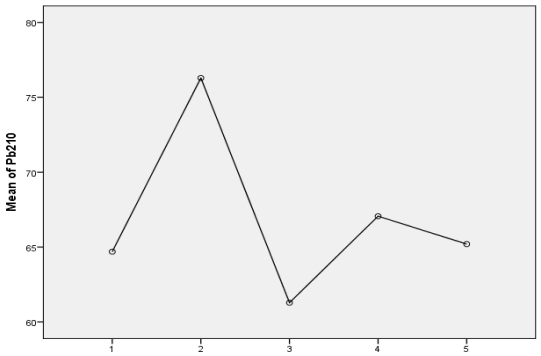
Table A12. Multiple Forest comparison Pb-210

Multiple Comparisons

Dependent Variable: Pb210 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 Light	2 Lt Medium	-11.599	10.203	1.000	-41.34	18.14
	3 Medium	3.407	13.890	1.000	-37.08	43.89
	4 Med Heavy	-2.370	11.063	1.000	-34.61	29.87
	5 Heavy	-.508	15.591	1.000	-45.95	44.93
2 Light Medium	1 Light	11.599	10.203	1.000	-18.14	41.34
	3 Medium	15.006	12.727	1.000	-22.09	52.10
	4 Med Heavy	9.229	9.562	1.000	-18.64	37.10
	5 Heavy	11.092	14.565	1.000	-31.36	53.54
3 Medium	1 Light	-3.407	13.890	1.000	-43.89	37.08
	2 Lt Medium	-15.006	12.727	1.000	-52.10	22.09
	4 Med Heavy	-5.777	13.426	1.000	-44.91	33.35
	5 Heavy	-3.914	17.348	1.000	-54.48	46.65
4 Med Heavy	1 Light	2.370	11.063	1.000	-29.87	34.61
	2 Lt Medium	-9.229	9.562	1.000	-37.10	18.64
	3 Medium	5.777	13.426	1.000	-33.35	44.91
	5 Heavy	1.863	15.180	1.000	-42.38	46.10
5 Heavy	1 Light	.508	15.591	1.000	-44.93	45.95
	2 Lt Medium	-11.092	14.565	1.000	-53.54	31.36
	3 Medium	3.914	17.348	1.000	-46.65	54.48
	4 Med Heavy	-1.863	15.180	1.000	-46.10	42.38



1 Light…….. Precipitation…… 5 Heavy

Table A13. Precipitation analysis Grassland only Pb-210

Oneway

Descriptives

Pb210 from initial data

Precipitation	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
2 Light Med	10	63.00	20.913	6.613	48.04	77.96	39	103
3 Medium	4	38.00	11.165	5.583	20.23	55.77	23	47
4 Md Heavy	10	63.00	31.266	9.887	40.63	85.37	28	142
5 Heavy	3	124.67	124.388	71.815	-184.33	433.66	45	268
Total	27	66.15	47.106	9.066	47.51	84.78	23	268

ANOVA

Pb210 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	13640.741	3	4546.914	2.374	.096
Within Groups	44052.667	23	1915.333		
Total	57693.407	26			

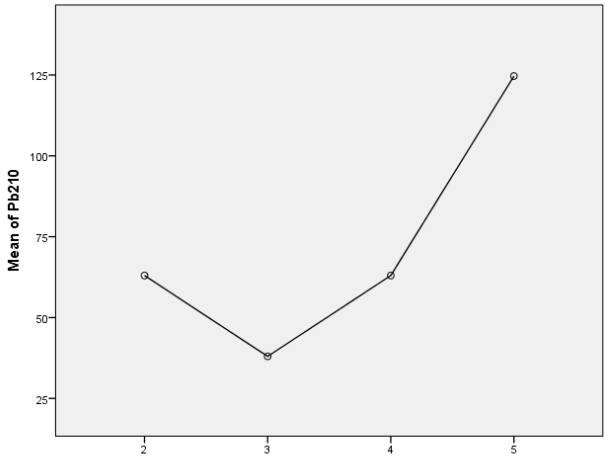
Table A14. Multiple Comparison Grassland Pb-210

Multiple Comparisons

Dependent Variable: Pb210 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2 Light Med	3 Medium	25.000	25.891	1.000	-49.73	99.73
	4 Med Heavy	.000	19.572	1.000	-56.49	56.49
	5 Heavy	-61.667	28.809	.259	-144.82	21.48
3 Medium	2 Lt Medium	-25.000	25.891	1.000	-99.73	49.73
	4 Med Heavy	-25.000	25.891	1.000	-99.73	49.73
	5 Heavy	-86.667	33.426	.098	-183.14	9.81
4 Med Heavy	2 Light Medium	.000	19.572	1.000	-56.49	56.49
	3 Medium	25.000	25.891	1.000	-49.73	99.73
	5 Heavy	-61.667	28.809	.259	-144.82	21.48
5 Heavy	2 Lt Medium	61.667	28.809	.259	-21.48	144.82
	3 Medium	86.667	33.426	.098	-9.81	183.14
	4 Med Heavy	61.667	28.809	.259	-21.48	144.82



1 Light……... Precipitation……..…… 5 Heavy

Table A15. Precipitation analysis Overall K40

Oneway

Descriptives

K40 from initial data

					95% Confidence Interval for Mean			
Precipitation	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Minimum	Maximum
1 Light	13	149.54	57.505	15.949	114.79	184.29	2	211
2 Md Hvy	34	161.26	51.563	8.843	143.27	179.26	2	261
3 Medium	11	146.27	72.322	21.806	97.69	194.86	13	220
4 Md Hvy	26	158.54	61.728	12.106	133.61	183.47	2	266
5 Heavy	8	159.38	38.704	13.684	127.02	191.73	109	207
Total	92	156.88	56.275	5.867	145.23	168.53	2	266

ANOVA

K40 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2713.318	4	678.330	.207	.934
Within Groups	285468.367	87	3281.246		
Total	288181.685	91			

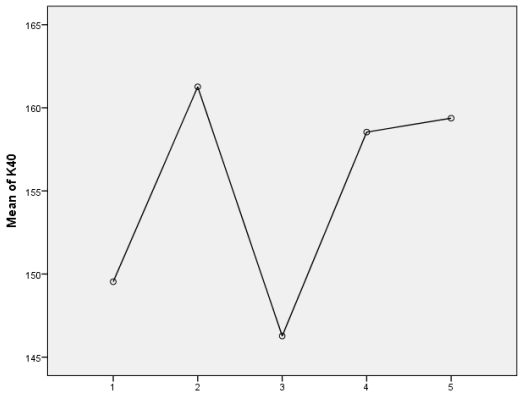
Table A16. Multiple Comparison – K-40

Multiple Comparisons

Dependent Variable: K40 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1 Light	2 Lt Medium	-11.726	18.679	1.000	-65.53	42.08
	3 Medium	3.266	23.467	1.000	-64.33	70.86
	4 Med Heavy	-9.000	19.458	1.000	-65.05	47.05
	5 Heavy	-9.837	25.740	1.000	-83.98	64.31
2 Light Medium	1 Light	11.726	18.679	1.000	-42.08	65.53
	3 Medium	14.992	19.870	1.000	-42.24	72.22
	4 Med Heavy	2.726	14.923	1.000	-40.26	45.71
	5 Heavy	1.890	22.509	1.000	-62.95	66.72
3 Medium	1 Light	-3.266	23.467	1.000	-70.86	64.33
	2 Lt Medium	-14.992	19.870	1.000	-72.22	42.24
	4 Med Heavy	-12.266	20.603	1.000	-71.61	47.08
	5 Heavy	-13.102	26.617	1.000	-89.77	63.56
4 Med Heavy	1 Light	9.000	19.458	1.000	-47.05	65.05
	2 Lt Medium	-2.726	14.923	1.000	-45.71	40.26
	3 Medium	12.266	20.603	1.000	-47.08	71.61
	5 Heavy	-.837	23.159	1.000	-67.54	65.87
5 Heavy	1 Light	9.837	25.740	1.000	-64.31	83.98
	2 Lt Medium	-1.890	22.509	1.000	-66.72	62.95
	3 Medium	13.102	26.617	1.000	-63.56	89.77
	4 Medium Heavy	.837	23.159	1.000	-65.87	67.54



1 Light... Precipitation…….. 5 Heavy

Table A16. Precipitation analysis Forest only K40

Oneway

Descriptives

K40 from initial data

Precipitation	N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
					Lower Bound	Upper Bound		
1 Light	13	149.54	57.505	15.949	114.79	184.29	2	211
2 Light Med	24	159.46	42.807	8.738	141.38	177.53	50	242
3 Medium	7	161.57	76.505	28.916	90.82	232.33	13	220
4 Md Hvy	16	146.25	50.908	12.727	119.12	173.38	2	210
5 Heavy	5	161.40	42.501	19.007	108.63	214.17	109	207
Total	65	154.60	50.872	6.310	141.99	167.21	2	242

ANOVA

K40 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	2586.497	4	646.624	.238	.916
Within Groups	163045.103	60	2717.418		
Total	165631.600	64			

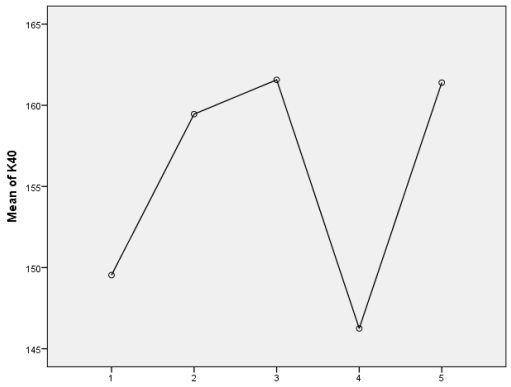
Table A17. Multiple Comparisons K-40

Multiple Comparisons

Dependent Variable: K40 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1 Light	2 Lt Medium	-9.920	17.952	1.000	-62.24	42.40
	3 Medium	-12.033	24.438	1.000	-83.26	59.19
	4 Med Heavy	3.288	19.465	1.000	-53.44	60.02
	5 Heavy	-11.862	27.432	1.000	-91.81	68.09
2 Light Medium	1 Light	9.920	17.952	1.000	-42.40	62.24
	3 Medium	-2.113	22.393	1.000	-67.38	63.15
	4 Med Heavy	13.208	16.825	1.000	-35.83	62.24
	5 Heavy	-1.942	25.626	1.000	-76.63	72.75
3 Medium	1 Light	12.033	24.438	1.000	-59.19	83.26
	2 Lt Medium	2.113	22.393	1.000	-63.15	67.38
	4 Med Heavy	15.321	23.623	1.000	-53.53	84.17
	5 Heavy	.171	30.524	1.000	-88.79	89.13
4 Med Heavy	1 Light	-3.288	19.465	1.000	-60.02	53.44
	2 Lt Medium	-13.208	16.825	1.000	-62.24	35.83
	3 Medium	-15.321	23.623	1.000	-84.17	53.53
	5 Heavy	-15.150	26.708	1.000	-92.99	62.69
5 Heavy	1 Light	11.862	27.432	1.000	-68.09	91.81
	2 Lt Medium	1.942	25.626	1.000	-72.75	76.63
	3 Medium	-.171	30.524	1.000	-89.13	88.79
	4 Med Heavy	15.150	26.708	1.000	-62.69	92.99



1 Light….. . Precipitation…… 5 Heavy

Table A17. Precipitation analysis Grassland only - K40

Oneway

Descriptives

K40 from initial data

					95% Confidence Interval for Mean			
Precipitation	N	Mean	Std. Deviation	Std. Error	Lower Bound	Upper Bound	Minimum	Maximum
2 Light Med	10	165.60	70.967	22.442	114.83	216.37	2	261
3 Medium	4	119.50	65.015	32.508	16.05	222.95	23	163
4 Md Heavy	10	178.20	74.611	23.594	124.83	231.57	2	266
5 Heavy	3	156.00	40.037	23.116	56.54	255.46	110	183
Total	27	162.37	68.331	13.150	135.34	189.40	2	266

ANOVA

K40 from initial data

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	10083.296	3	3361.099	.694	.565
Within Groups	111315.000	23	4839.783		
Total	121398.296	26			

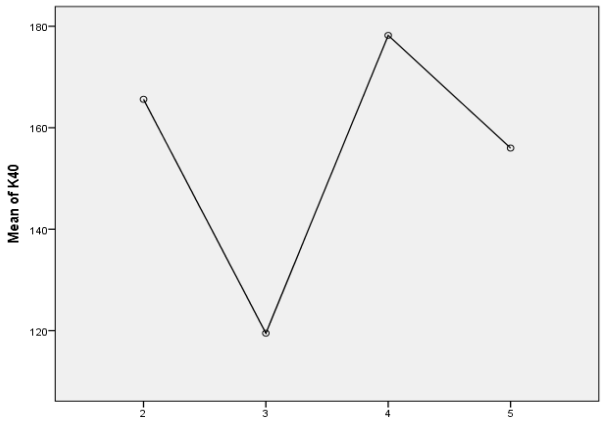
Table A18. Multiple Comparisons K-40

Multiple Comparisons

Dependent Variable: K40 from initial data

Bonferroni

Precipitation	Precipitation	Mean Difference	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
2 Light Medium	3 Medium	46.100	41.157	1.000	-72.69	164.89
	4 Med Heavy	-12.600	31.112	1.000	-102.40	77.20
	5 Heavy	9.600	45.796	1.000	-122.58	141.78
3 Medium	2 Lt Medium	-46.100	41.157	1.000	-164.89	72.69
	4 Med Heavy	-58.700	41.157	1.000	-177.49	60.09
	5 Heavy	-36.500	53.134	1.000	-189.86	116.86
4 Med Heavy	2 Lt Medium	12.600	31.112	1.000	-77.20	102.40
	3 Medium	58.700	41.157	1.000	-60.09	177.49
	5 Heavy	22.200	45.796	1.000	-109.98	154.38
5 Heavy	2 Lt Medium	-9.600	45.796	1.000	-141.78	122.58
	3 Medium	36.500	53.134	1.000	-116.86	189.86
	4 Med Heavy	-22.200	45.796	1.000	-154.38	109.98



1 Light…….. Precipitation…….. 5 Heavy

Table A19. Forest vs. Controls Cs137

T-Test from initial data

Group Statistics

	F 1 G2	N	Mean	Std. Deviation	Std. Error Mean
Cs137	Forest	65	81.02	34.537	4.284
	Control	4	10.00	2.449	1.225

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
From initial data		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Cs137	Equal variances assumed	3.430	.068	4.083	67	.000	71.015	17.391	36.303	105.728
	Equal variances not assumed			15.939	65.547	.000	71.015	4.455	62.119	79.912

Significantly higher Forest level; than control level.

Table A20. Grassland vs. Control Cs137

T-Test

Group Statistics

	F 1 G2	N	Mean	Std. Deviation	Std. Error Mean
Cs137	Grassland	27	40.04	26.828	5.163
	Control	4	10.00	2.449	1.225

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
From initial data		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Cs137	Equal variances assumed	6.611	.016	2.206	29	.035	30.037	13.616	2.189	57.885
	Equal variances not assumed			5.661	28.234	.000	30.037	5.306	19.172	40.902

Significantly higher Grassland level; than control level.

Table A21. Forest vs Control Pb210

T-Test

Group Statistics from initial data

	F 1 G2	N	Mean	Std. Deviation	Std. Error Mean
Pb210	Forest	65	69.23	29.243	3.627
	Control	4	49.25	9.394	4.697

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
From initial data		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Pb210	Equal variances assumed	1.472	.229	1.354	67	.180	19.981	14.759	-9.479	49.441
	Equal variances not assumed			3.367	7.520	.011	19.981	5.935	6.142	33.820

Not a significant difference.

Table A22. Grassland vs. Control Pb-210

T-Test

Group Statistic from initial data

	F 1 G2	N	Mean	Std. Deviation	Std. Error Mean
Pb210	Grassland	27	66.15	47.106	9.066
	Control	4	49.25	9.394	4.697

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
From initial data		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
Pb210	Equal variances assumed	.988	.329	.706	29	.486	16.898	23.951	-32.088	65.884
	Equal variances not assumed			1.655	25.750	.110	16.898	10.210	-4.099	37.895

Not a significant difference.

Table A23. Forest vs. Control K40

T-Test

Group Statistics from initial data

	F 1 G2	N	Mean	Std. Deviation	Std. Error Mean
K40	Forest	65	154.60	50.872	6.310
	Control	4	49.75	33.570	16.785

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
From initial data		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
K40	Equal variances assumed	.684	.411	4.052	67	.000	104.850	25.874	53.206	156.494
	Equal variances not assumed			5.847	3.904	.005	104.850	17.932	54.578	155.122

Significantly higher Forest level; than control level.

Table A24. Forest vs. Grassland K40

T-Test

Group Statistics from initial data

	F 1 G2	N	Mean	Std. Deviation	Std. Error Mean
K40	Grassland	27	162.37	68.331	13.150
	Control	4	49.75	33.570	16.785

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
From initial data		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
K40	Equal variances assumed	.966	.334	3.205	29	.003	112.620	35.143	40.745	184.496
	Equal variances not assumed			5.282	7.488	.001	112.620	21.323	62.858	162.383

Significantly higher Grassland level; than control level.

A25. Permit from Indiana Division of Nature Preserves (2 pages).

Division of Nature Preserves

RESEARCH & COLLECTING PERMIT

This permit, **(Identification No. NP17-50)** authorized on **June 1, 2017** and expiring on **December 31, 2017,** is issued to **Richard Whitman,** Doctoral Candidate, Natural Resource and Environmental Management/EMHS, Ball State University, Muncie, IN. The holder, and/or any assistants working under his direction, is **authorized to enter Douglas Woods Nature Preserve (TNC) and Boot Lake Nature Preserve (City of Elkhart) for the purpose of collecting soil samples.**

This permit is issued with the following conditions:

1. You shall be responsible for all and any damage to these properties while conducting your research.
2. Being aware of the nature and potential hazards of your activity, you, and any assistants accompanying you, do hereby release and hold harmless The Nature Conservancy, the City of Elkhart, and the State of Indiana, their officers, agents and employees from any and all liability for death, injury or loss or damage to property incurred in connection with the use of this permit.
3. This permit must be carried by the holder at all times while at the above mentioned properties for purposes authorized herein.
4. Research/Collecting should be conducted at times, if possible, when such activities cannot be observed by visitors to the areas.
5. All field equipment and gear (including footwear and clothing) must be cleaned prior to each onsite visit to prevent contamination and introduction of non-native exotic species.
6. **From each property, two small cylinder soil samples (approximately the size of a 1-liter bottle), may be removed to collect the material between 2 and 10 cm in depth. Remaining material will be replaced where excavated.**
7. No specimen of flora, fauna, water, mineral or artifact shall be disturbed or removed from the properties, except as authorized herein.
8. The Nature Conservancy, the City of Elkhart, and the DNR Division of Nature Preserves are to **receive a complete report from you,** which lists in detail the results of your study. Your report should arrive in a timely fashion as soon as possible after the permit expires.
9. Publication resulting from this study must not reveal property names or their locations. Failure to abide by this condition may result in suspension of future research and/or collecting privileges. If your report is published, a reprint copy of the journal article must be sent to these offices.
10. The authority for this permit may be terminated at any time at the discretion of these offices. Upon expiration of this permit, application may be made for a new permit. Permit renewals will be made based on our judgement of your performance and the value of the work completed under the previous permit. The submission of a report to these offices will be of utmost importance in the further consideration of permit renewal.

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